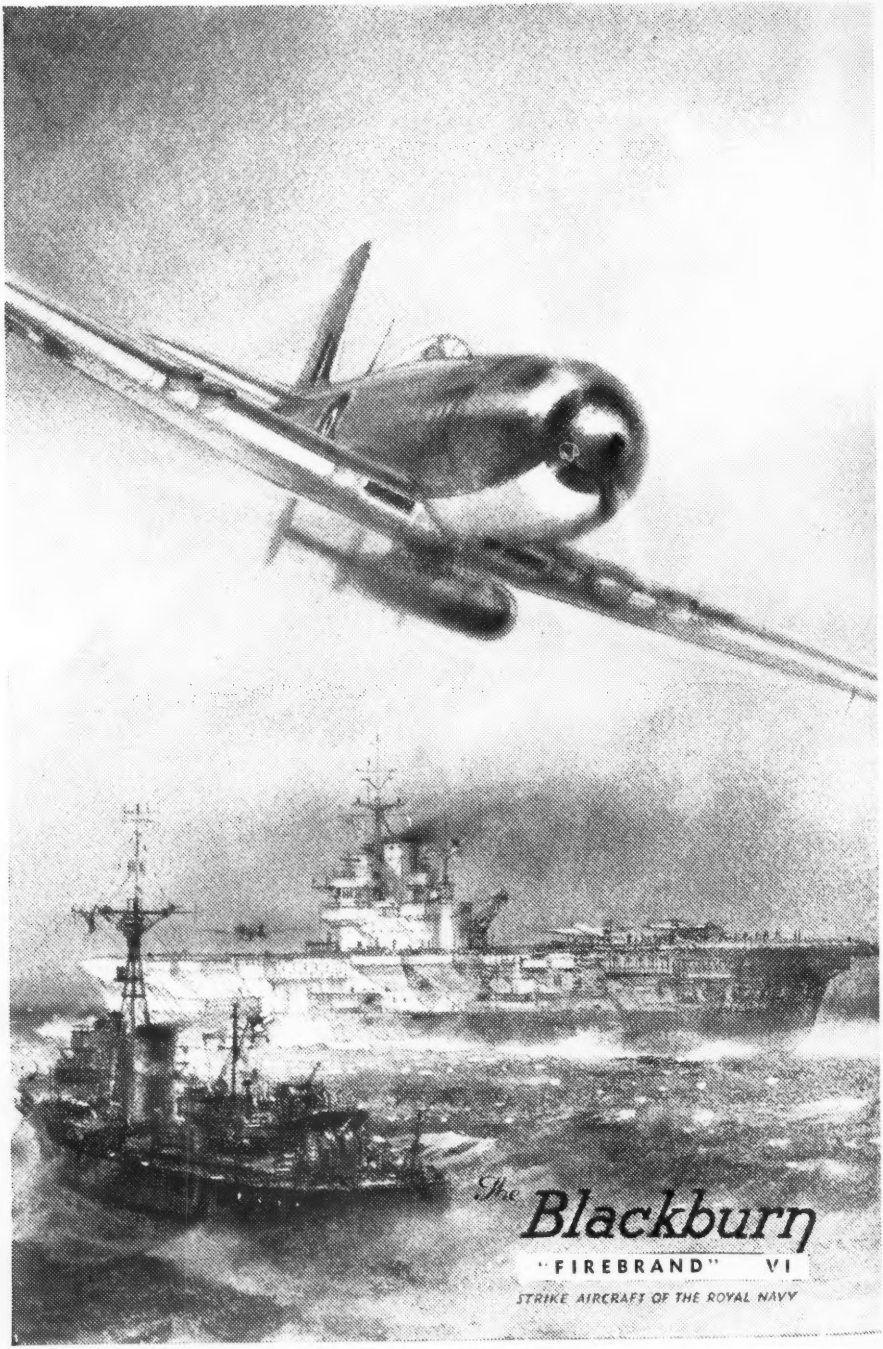
The Journal of the ROYAL AERONAUTICAL SOCIETY

ANGLO-AMERICAN AERONAUTICAL CONFERENCE

See MONTHLY NOTICES

JUNE 1947 · NO 438 · VOL 51


The Blackburn
"FIREBRAND" VI
STRIKE AIRCRAFT OF THE ROYAL NAVY

THE ROYAL AERONAUTICAL SOCIETY
4 HAMILTON PLACE, PICCADILLY, LONDON, W.1

JUNE NOTICES 1947

JOURNAL PREMIUM AWARDS

The Council have set aside an annual sum of £250 for the award of premiums for papers published in the *Journal* and the Council hope that members (or non-members) will contribute papers on their own special subjects.

ANGLO-AMERICAN AERONAUTICAL CONFERENCE

The attention of members is drawn to the application form, in this issue of the Journal, for membership of the Anglo-American Aeronautical Conference which will be held in September next.

Membership of the Conference will be limited in numbers and it is advisable to make application as soon as possible.

GARDEN PARTY

The Society's Annual Garden Party will be held on Sunday, 14th September 1947, at Radlett Aerodrome, by kind permission of the President, Sir Frederick Handley Page.

The Society of British Aircraft Constructors have again generously offered to keep their Static and Flying Display in being for the day.

Application forms for tickets will be issued with the July Journal and no previous application for tickets can be considered.

OFFICE HOURS

The offices of the Society are now open from 9 a.m. to 5 p.m., Monday to Friday, and closed on Saturday *except* for the Library, which is open from 9.30 to 12.30 p.m.

CONTENTS OF THE JUNE JOURNAL

The 35th Wilbur Wright Memorial Lecture, The Development of All-Wing Aircraft, by John K. Northrop.

A Review of Production Difficulties in Relation to Aircraft Design, by C. E. Fielding, O.B.E., A.F.R.Ae.S., M.I.P.E.

The Theory of Limit Design Applied to Magnesium Alloy and Aluminium Alloy Structures, by Filadelfo Panlilio.

MEDALS AND AWARDS

The following medals have been awarded by the Council:—

SIMMS GOLD MEDAL

Awarded annually for the best paper read in any year before the Society on any science allied to aeronautics, meteorology, wireless telegraphy, instruments. To—

Professor L. Aitchison, D.Met., B.Sc., F.R.I.C., F.R.Ae.S., Professor of Industrial Metallurgy at Birmingham University, for his paper "Aeronautics and the Metallurgist."

NOTICES

THE GEORGE TAYLOR (OF AUSTRALIA) GOLD MEDAL

Awarded annually, at the discretion of the Council, for the most valuable paper submitted or read during the previous session. To—

Professor A. R. Collar, M.A., D.Sc., F.R.Ae.S., Sir George White Professor of Aeronautical Engineering, Bristol University, for his paper "Aeroelastic Problems at High Speed."

WAKEFIELD GOLD MEDAL

Awarded annually to the designer of any invention or apparatus tending towards safety in flying, and open to members or non-members. To—

Mr. Edwin Link, the inventor of the Link Trainer.

SOCIETY'S SILVER MEDAL

Awarded, at the discretion of the Council, for some advance in aeronautical design. To—

Mr. W. G. Carter, F.R.Ae.S., Chief Designer, Gloster Aircraft Co. Ltd., for his work on the development and design of jet-propelled aircraft.

R.38 MEMORIAL PRIZE

Offered annually for the best paper received by the Society on some subject of a technical nature in the science of aeronautics, preference being given to papers which relate to airships. To—

Mr. J. K. Hardy, of the Royal Aircraft Establishment, for his paper "Protection of Aircraft Against Ice."

EDWARD BUSK MEMORIAL PRIZE

Offered annually for the best paper received by the Society on some subject of a technical nature in connection with aeroplanes (including seaplanes). To—

Mr. J. Smith, C.B.E., A.M.I.A.E., F.R.Ae.S., Chief Designer, Vickers-Armstrongs Ltd., Supermarine Works, for his paper "The Evolution of the Spitfire."

JOURNAL PREMIUM AWARDS

The Council have made the following premium awards for 1946 for papers published in the Journal:—

G. H. Lee, A.R.C.S., B.Sc., D.I.C., A.F.R.Ae.S., The Case for the Tailless Aircraft. Twenty Guineas. November 1946 Journal.

G. V. Raynor, M.A., D.Phil., Beryllium, Beryllium Alloys and the Theoretical Principles Affecting Alloy Formation with Beryllium. Fifteen Guineas. May 1946 Journal.

A. P. West, A.F.R.Ae.S., The Design and Production of Japanese Military Aircraft. Fifteen Guineas. July 1946 Journal.

P. A. Wills, C.B.E., Method of Accident Investigation and Prevention Adopted by Air Transport Auxiliary. Fifteen Guineas. June 1946 Journal.

W. J. Goodey, M.A., A.F.R.Ae.S., The Stresses in a Circular Fuselage. Ten Guineas. November 1946 Journal.

W. Hampton, Graduate, The de Havilland Wing Test Rig. Ten Guineas. April 1946 Journal.

HONOURS

Air Marshal Sir Ralph Squire Sorley, Fellow of the Society, has been awarded the Legion of Merit, Degree of Commander, by the American Government for exceptionally meritorious service on military equipment. The citation adds: "Through his outstanding professional knowledge and spirit of co-operation, Air Marshal Sorley contributed immeasurably to the success of the Allied war effort."

CLOSING OF LIBRARY FOR STOCKTAKING DURING AUGUST

The Library will be closed for stocktaking from 11th to 23rd August inclusive. Members are requested to return all books which they have on loan from the Library *not later than Saturday, 9th August.*

NATIONAL GLIDING CONTESTS

The British Gliding Association will hold the National Gliding Contests at Bramcote Aerodrome between 21st and 29th June. Full details of the Contests may be obtained from the Association at Londonderry House, 19 Park Lane, W.1.

These Contests are a preliminary to the important International Gliding Contests of 1948 and the Association hopes that all those interested in gliding, and indeed in aviation generally, will help by giving such donations and gifts as they can towards the heavy expenses and necessary equipment which will be wanted. All donations and gifts should be sent to the Secretary of the British Gliding Association at Londonderry House.

LIST OF MEMBERS

A List of Members of the Society is being prepared. Members should already have received a special post card on which they are asked to fill in their name, grade of membership of the Society, rank or title (if any), any letters to which they are entitled (*e.g.*, F.R.S., M.I.Mech.E., etc.) and address, as they wish them to appear in the List.

The Secretary will be glad if members will return the cards, filled in, as soon as possible please.

THE LUTON BRANCH

Mr. D. A. R. Clark, Chairman of the Luton Branch, has resigned on his appointment as Principal at the Middlesbrough Technical College. The office is now taken by Mr. K. H. Greenly.

GRADUATES' AND STUDENTS' SECTION

A visit has been arranged to the National Physical Laboratory, Teddington, on Saturday, 5th July, at 10 a.m. Applications to attend this visit should be sent to the Hon. Secretary, J. G. Roxburgh, 62 Fitzjohns Avenue, London, N.W.3.

ELECTION OF MEMBERS

The following members have been elected recently:—

Fellows (from Associate Fellows)

Charles Herbert Colvin, Robert Graham, George Jackson Mead, Frederick William Meredith, Harold Charles Pritchard, Reginald Herbert Schlotel, George Temple (from Companion), Robert Hicks Walmsley.

Associate Fellows

Harold Rennesson Ashley, Peter Blandford (from Associate), Henry George Bloss, Denis Harold Bradney, Claude Templar Brown, George Henry Fitzroy Brown, Louis Frederick Campion, Roy Samuel Charles Cater, Samuel Child, Cyril Robert Creighton, William Francis Crewdson, William Henry Darlington, John Horace Hamilton Davison, Laurence Alfred Egglesfield, Ronald Sidney George Elkin (from Associate), Gordon Drummond Frier (from Graduate), William Gerald Glendinning, Gordon William Thomas Gray (from Associate), Joseph Walter Griffiths, James Henry Halpin, Donald Arthur Hancock (from Student), Dennis John Higton (from Graduate), Edgar Vincent King, Leonard William Larke (from Graduate), Conrad Albert Mann (from Associate), Francis George Manning, Ronald Sinclair Massey, David Edward Morris, Leslie Alan Nevard (from Graduate), Ronald Herbert Ponsford Nott (from Student), Frank Pawling (from Graduate), Kenneth Cyril Peggs, George Brian Gibbon Potter, Edward Jreneusz Raczynski, Raymond George Ralph, Arthur George Rodd (from Graduate), Allenby William Rogers (from Graduate), Basil Saravanos (from Companion), Norman Ellis Sweeting, Donald Charles Whittley (from Student), Dennis Wilde (from Graduate), Christopher Frederick Henry Wright.

Associates

Charles Herbert Allen, Frank Camfield Aylesbury, Ted Bate, Gordon Don Bedson, Leslie John Brooks, Percy Philip Brown, Harold Edward McKenzie Cann, Richard Arthur Norman Cater, John Richard Claydon, Kenneth Cecil Cornish, David George Sinclair Cotter, Gerard John Regis Leo D'Erlanger, Arthur Ernest Dunlop, Godfrey Jarvis Earnshaw, Irvin Rennison Foster, Edward James Gregory (from Graduate), Carlo Domenico Griseri, William Philip Clifford Hagger, Arthur Sydney Herbert, Ralph Frederick Jenson, Jack Morgan Kidman, Harry Philip Langworthy, Edward John Mann, John Marshall, Eric John Martin, Frederick John Nathan, Jack Lamport-Newton, Harry Palfreman, Charles Conrad Rivers, Conyers Rutter (from Student), Stuart Sendall-King, Philip Jeffrey Smith, Victor Thomas George Stevenson, Victor Francis Williams, Evan Wright, Norman Percy Wright.

Graduates

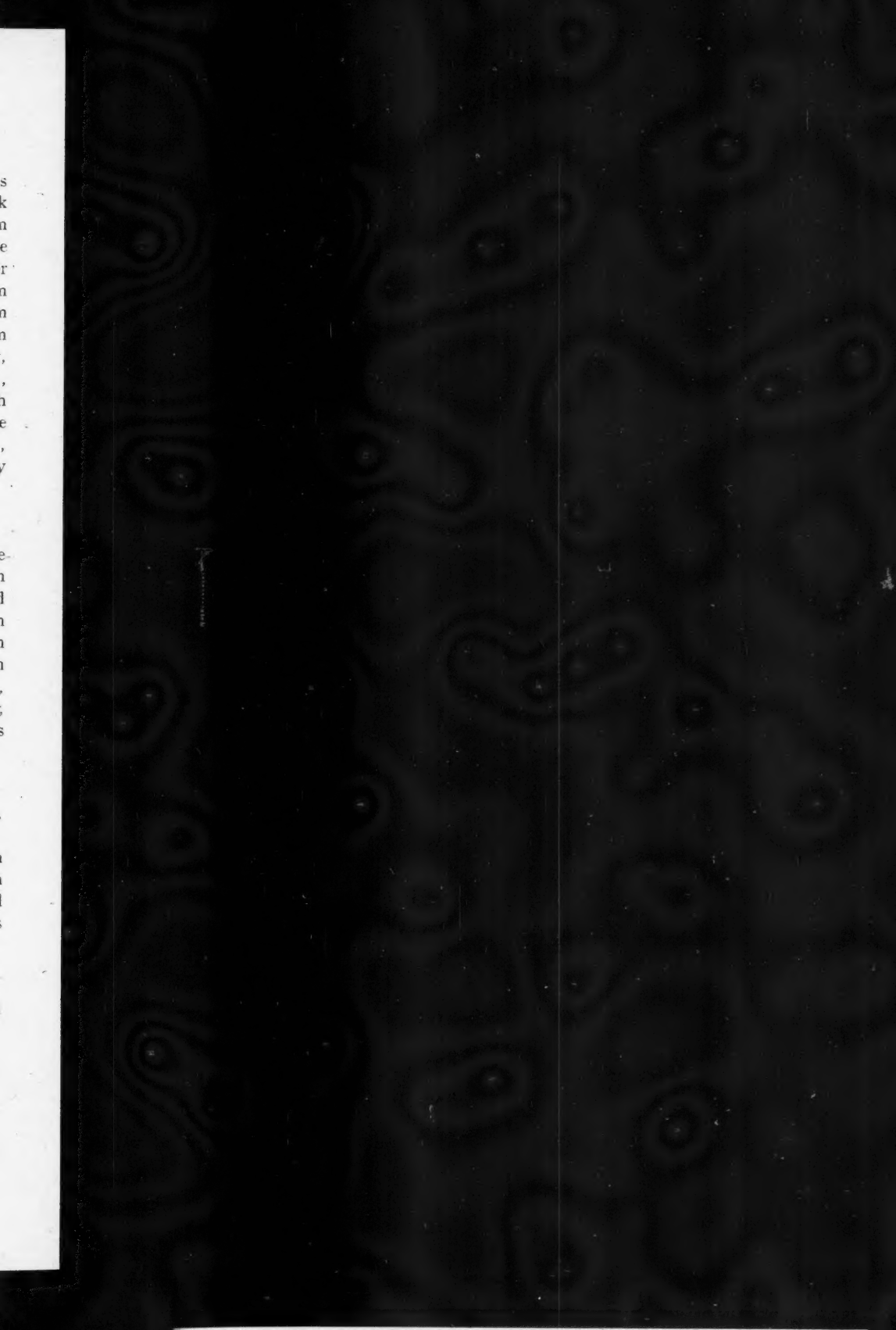
Frank Harry Bond (from Student), Andrew Dick, Edward Mark Dowlen (from Student), Reginald Charles William Eyre, Raymond William Edward Graham (from Student), Thomas William Horn (from Student), Donald Russell Jones (from Student), Hugh Milne Kerr, George Geoffrey Legg (from Student), Bernard Francis Martin, Harry Allan Pugh, Victor Alfred Baden Rogers (from Student), Ivor Schofield (from Student), Raymond Kenneth Peter Stevens, Leonard Stockdale (from Student), John Stringer, Peter James Windibank (from Student), Michael Thomas Witts.

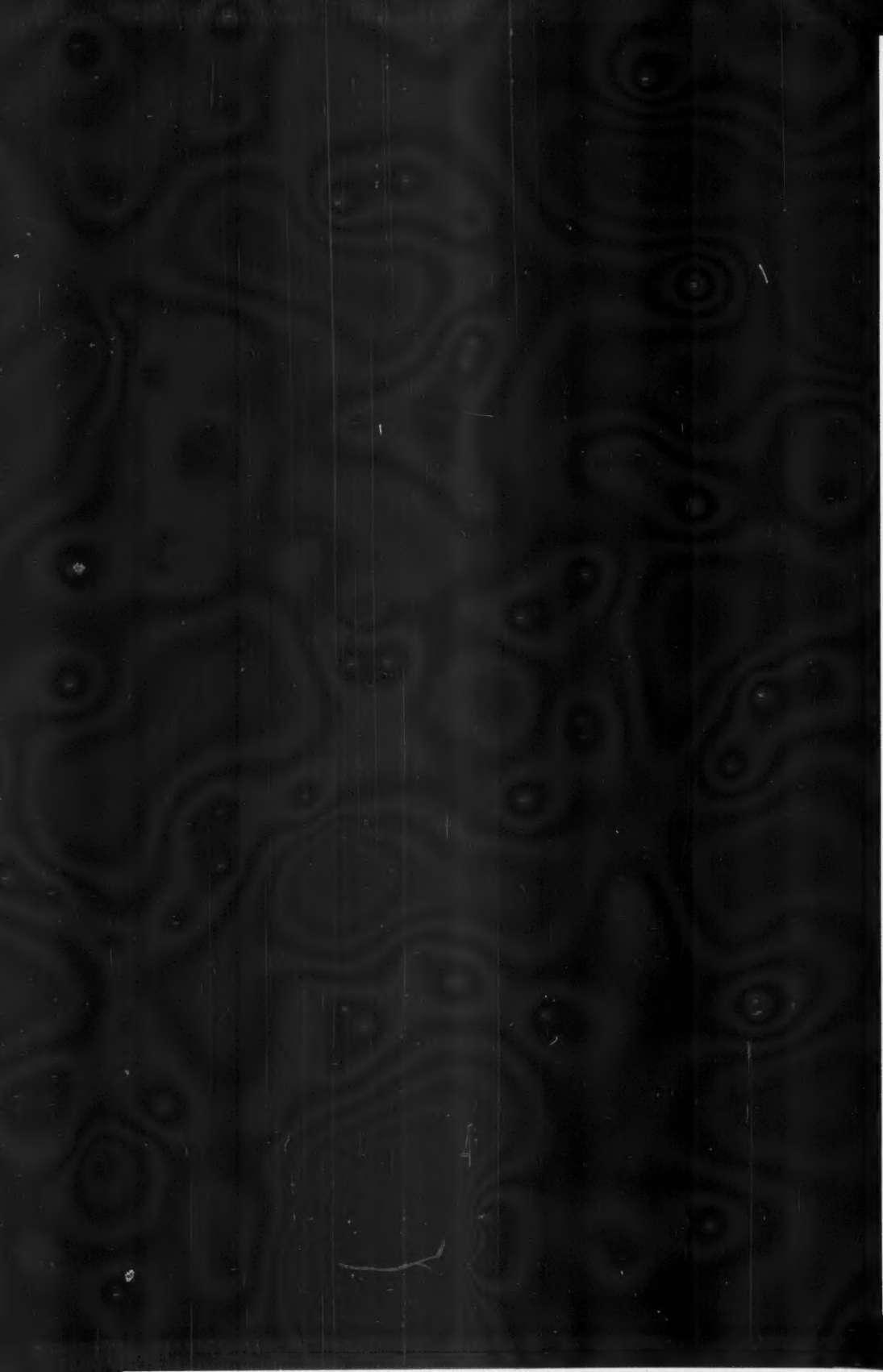
Students

John Edward Alasia, Richard Graham Bickerton, Thomas Brindley Booth, Peter Langrill Carberry, Ronald Scott Challender, James Patrick Clement Clark, James Roy Combley, Godfrey Harold Ellis, Royal George Harmer, John Frederick Lay, Francis John Mearing, Barry George Newman, Charles Peter Seward Popkin, Charles Frederick Thomas, Bernard Charles Warren, Arthur Frank Albert Watts, Joseph Edward Williams.

Companions

Robert Alexander Grant, Gerard Joseph Mary O'Reilly, Alec Ryden Walley (from Student), Peter John West.





ACKNOWLEDGMENTS

The Council acknowledge with grateful thanks the gift of photographs from Group Capt. R. McIntyre, Associate Fellow, D. B. Peter, Esq., Associate Fellow, and H. R. Trost, Esq.; also back numbers of the Journal from Miss M. de Bunsen, Companion, Wing Commander S. T. Freeman, Associate Fellow, D. Napier & Son Ltd. (through W. G. Goodwin), and The Rt. Hon. Lord Sempill, Fellow.

ADDITIONS TO THE LIBRARY

Pamphlets in italics with location reference following in brackets. Books marked * or ** may not be taken out on loan.

B.c.72—Story of the Helicopter. Devon Francis. Coward McCann, New York. 1946.

BB.d.36—Hymatic in War and Peace. Hymatic Engineering, Redditch.

BB.f.123—Introduction to Aeronautics. C. F. Toms. Griffin. 1947.

E.c.31—Aircraft Strength of Materials. H. D. Conway. Chapman & Hall. 1947.

E.d.29 and 30—Attrezatura d'Officina. Vols. I and II. Aldo Berruti. Viglongo, Turin. 1947.

E.h.8—The Aircraft Builders. Nigel Balchin. H.M.S.O. 1947.

G.e.A.117—L'Aluminium dans les lignes électriques aériennes et les postes de transformation. L'Aluminium Francais, Paris. 1937.

G.e.K.10—The Fireproofing of Fabrics. J. E. Ramsbottom. H.M.S.O. 1947.

I.d.9—Applied Elasticity. John Prescott. Dover Publications, New York. 1946.

J.g.216—Tropical and Equatorial Meteorology. Maurice A. Garbell. Pitman. 1947.

L.d.116—*Notices to Airmen*, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118.

R.c.289—Artificial and Natural Flight. Hiram Maxim. Whittaker. 1908.

V.7/29—Transactions of the Institution of Naval Architects. Volume 88. 1946. Institution of Naval Architects.

X.b.155—Whitaker's Almanac. 1947.

X.c.157—B.B.C. German Vocabulary. L. Hamilton. Longmans Green. 1947.

A.R.C. Reports and Memoranda

1980—*A theoretical investigation of dynamic stability with free elevators. J. Whatham and H. M. Lyon.*

2005—*Tunnel interference at compressibility speeds, using the flexible walls of the rectangular high-speed tunnel. C. N. H. Lock and J. A. Beavan.*

2089—*Two-dimensional constant velocity ducts. N. J. S. Hughes.*

2035—*Strip theory method of calculation for airscrews on high-speed aeroplanes. R. C. Pankhurst and J. F. C. Conn.*

2051—*Contra-rotating airscrew experiments for Hispano-Suiza* 1939. *J. Valensi.*

2063—*The application of a "Wattmeter" Harmonic Analyser to the measurement of aerodynamic damping for pitching oscillations. J. B. Bratt, K. C. Wight and V. J. Tilley.*

2076—*Notes and exploratory experiments on the aerodynamic balancing of controls. H. B. Irving, A. S. Batson and J. H. Warsap.*

2092—*The determination of propeller power* coefficients by flight tests on a Spitfire Vc *aircraft. Flight Lieutenant Majcherckyk.*

2081—*Free motion of a stable glider in an atmosphere of variable density.* *W. J. Duncan.*

2082—*The linkage by the escalator process of crankshaft propeller geared systems.* *J. Morris.*

2102—*Note on methods at the National Physical Laboratory and in the U.S.A. for calculating the profile drag at high speeds from pitot traverse measurements.* *J. A. Beavan.*

2109—*Tests on an aerofoil with 20 per cent. slotted flap and an auxiliary flap in the compressed air tunnel.* *R. Jones and A. H. Bell.*

The following reports have also been received:—

National Luchtvaartlaboratorium, Amsterdam

Reports Nos. S.280, S.314 and S.319.

L'Aluminium Francais

Four reports.

British Intelligence Objectives Sub-Committee

B.I.O.S. Final Reports Nos. 1179, 1180 and 881, Item No. 27.

F.I.A.T. Final Reports Nos. 594, 986 and 446.

J. LAURENCE PRITCHARD,
Secretary.

Made and Printed in Great Britain by the Lewes Press, Lewes, Sussex

THE ROYAL AERONAUTICAL SOCIETY

ANGLO-AMERICAN AERONAUTICAL CONFERENCE

The preliminary arrangements for the Anglo-American Aeronautical Conference, convened by the Royal Aeronautical Society and the Institute of the Aeronautical Sciences, have now been made.

The Conference will be held from September 3rd to September 6th 1947 at the Victoria Halls, Bloomsbury Square, W.C.1. Papers will be prepared by the leading aeronautical authorities in this country and the United States and in all some twenty separate papers will be read. Generally, there will be four papers in each morning session (two being read at the same time in different halls) and two or more in the afternoon. On the morning of the final day of the Conference the general conclusions will be summarised and a discussion will take place on the technical trends of the next few years.

At each session the lecturer will give a twenty minute summary of his paper which will be followed by a discussion. A printed copy of each paper, as it will be read, will be sent to all members of the Conference in advance of the opening date. The complete papers for the Conference, together with the discussions, will be published as a separate volume as soon as possible after the conference.

P.T.O.

Only members of the Royal Aeronautical Society and/or the Institute of the Aeronautical Sciences will be admitted as members of the Conference. Membership will be limited in number and application should be made as soon as possible on the form attached to this note, and in no case later than July 31st 1947. The membership fee is two guineas.

When a member has been enrolled, he will receive copies of all the papers to be read and details of all other arrangements as soon as they are known.

A Reception will be held at the Society's headquarters, 4 Hamilton Place, W.1 on Tuesday September 2nd for the Conference delegates and a Garden Party to the delegates and their ladies will be given by the President at Limes House, Stanmore on Sunday September 7th 1947. On Tuesday September 9th a dinner will be held at Guildhall at which the Lord Mayor has kindly agreed to be present. Although this dinner will also be open to members of the Society and their ladies, preference will be given to members of the Conference and their ladies in the allocation of tickets. An application form for tickets (£2 . 2 . 0 each) for the Dinner at Guildhall will be sent on request.

ANGLO-AMERICAN
AERONAUTICAL CONFERENCE
September 3rd—September 6th 1947

Date.....

To the Secretary,
The Royal Aeronautical Society,
4 Hamilton Place,
London, W.1

Please enrol me as a member of the Anglo-American Aeronautical Conference. I enclose a remittance for Two Guineas. (Remittances should be made payable to AERIAL SCIENCE LIMITED).

BLOCK LETTERS PLEASE

NAME.....

GRADE.....

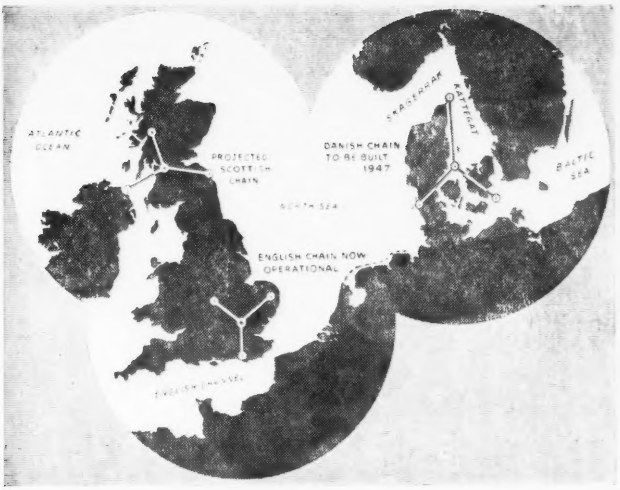
ADDRESS.....

.....

.....

* Please send me an application form for tickets for the Dinner at Guildhall on September 9th 1947.

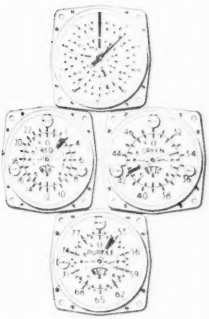
* Strike out if you do not wish to attend dinner.



This map shows the three Decca Navigator Chains of stations. Each covers an area with a radius of 300 miles. The intersecting circles show the wide operational area.

Decca Navigator coverage

in Western Europe to be ***750,000 square miles***



A typical layout of Decca Decometers including the new Lane Identification differential meter.

Within twelve months the service area of the Decca Navigator system in Western Europe will be 750,000 square miles. The English Chain of Decca transmitters, situated in the Home Counties, has been in continuous operation for many months. Extensive and closely observed practical trials utilising its transmissions have resulted in the system receiving the approval of the Ministry of Transport.

Following the approval of the Danish Government, a Decca Chain of transmitters will be erected in their country, and a further Chain is projected for Scotland.

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FLIGHT (weekly) provides the most authentic information on world aeronautical affairs. It covers every aspect of development and progress in aircraft and power unit design and operation. AIRCRAFT PRODUCTION (monthly) is the journal of the aircraft manufacturing industry, specialising in tools and works production processes.

The editorial staffs of each journal are experts in their own particular sphere, with unrivalled experience and resources. Both journals serve the interests of all concerned with the future progress of British aviation. Technical information is supplemented by brilliant functional drawings. Circulation is world-wide. Annual subscriptions (Home and Overseas) FLIGHT £3 1s. 0d., AIRCRAFT PRODUCTION £1 14s. 6d.

Published in conjunction with these journals, FLIGHT HANDBOOK (212 pages, 7 6 net) is essentially a manual for the student, whilst GAS TURBINES AND JET PROPULSION (272 pages, 12 6 net) by G. Geoffrey Smith, has been widely adopted as the standard text on the subject by Universities, Technical Institutions and Training Centres everywhere.

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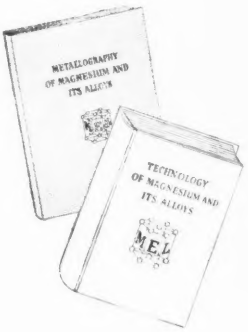
"Technology of Magnesium and Its Alloys". 512 pages, size Royal 8vo, illustrated with 524 photographs and diagrams. Price 30 - plus 7d. postage. (Prospectus available on request.)

"Metallography of Magnesium and Its Alloys". 118 pages, size Royal 8vo, with 225 photographic illustrations. Price 15 - plus 6d. postage. (Prospectus available on request.)

Other publications available, without charge, cover properties, casting design, manipulation etc.



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Networks of "GEE" stations already exist, covering most of the United Kingdom and a large part of Europe, and our Government have recently announced their intention of making available to those liberated countries requiring it complete ground installations, as well as a limited number of airborne installations from surplus stocks, thus providing them with temporary navigation facilities. The British European Airways, after thoroughly examining all competitive navigational aids, recently announced their decision to adopt "GEE." They are planning its introduction into all of their aircraft, in order that their equipment may be brought up to the only known proven system readily available for safe modern operation.

Extract from an address made by Mr. I. A. Macauley, Chairman of A. C. Cossor Ltd., on 14th August, 1946, at the company's 8th General Meeting.

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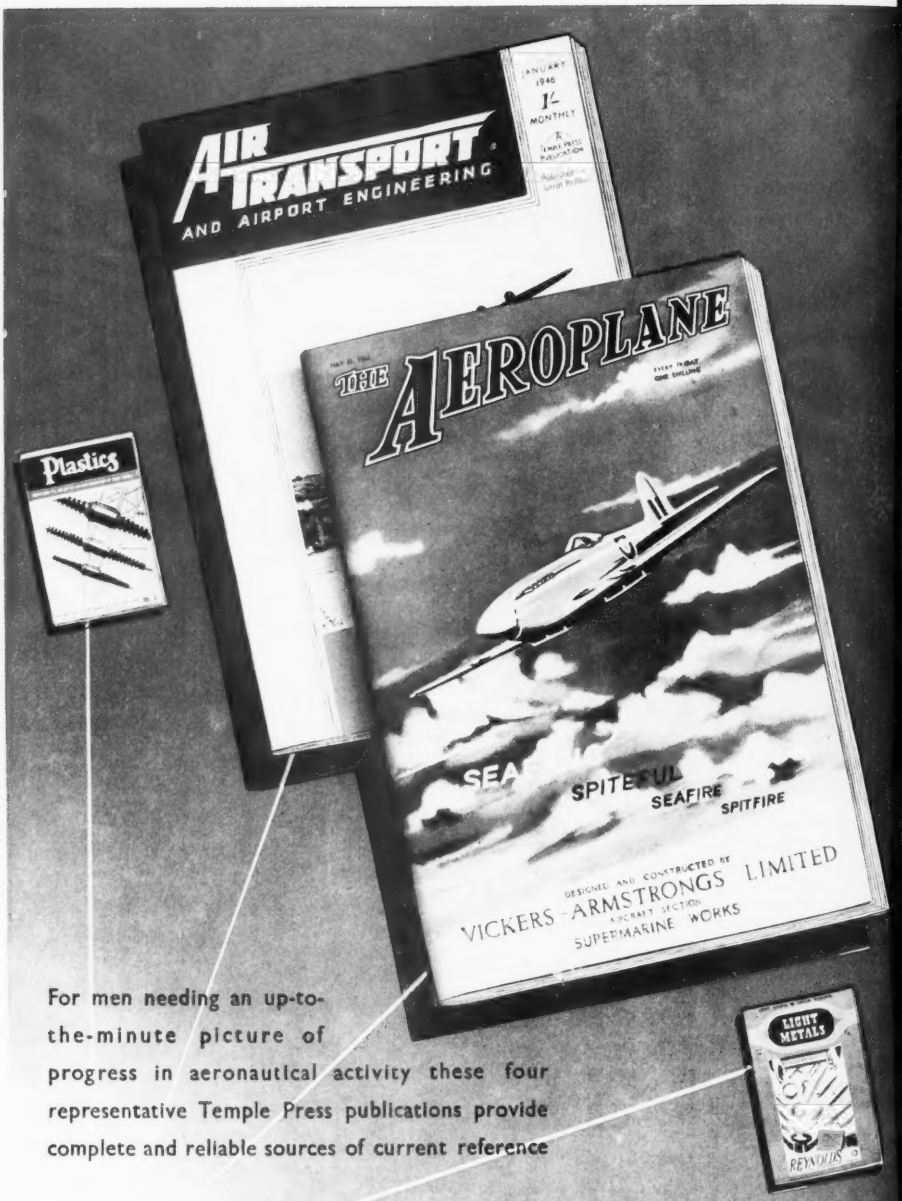

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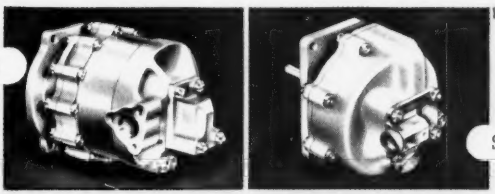

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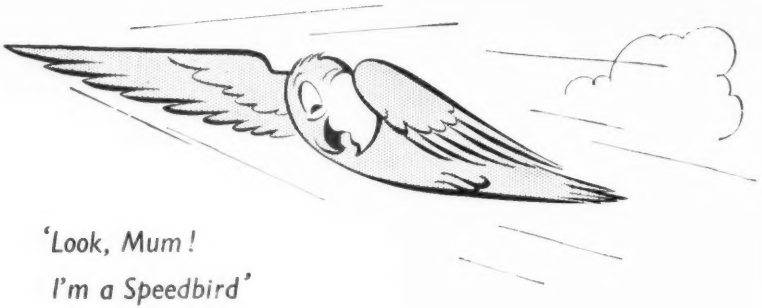

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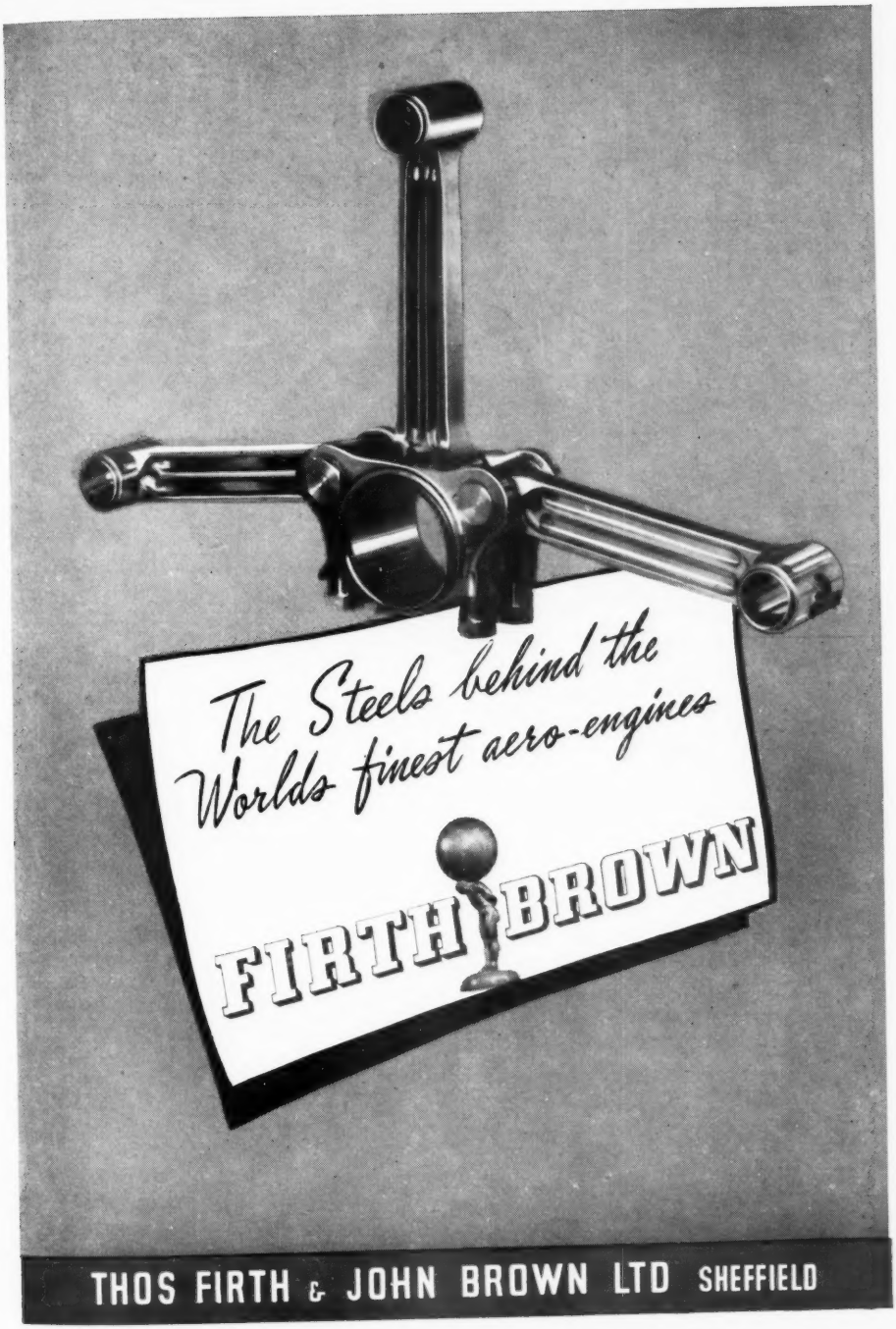
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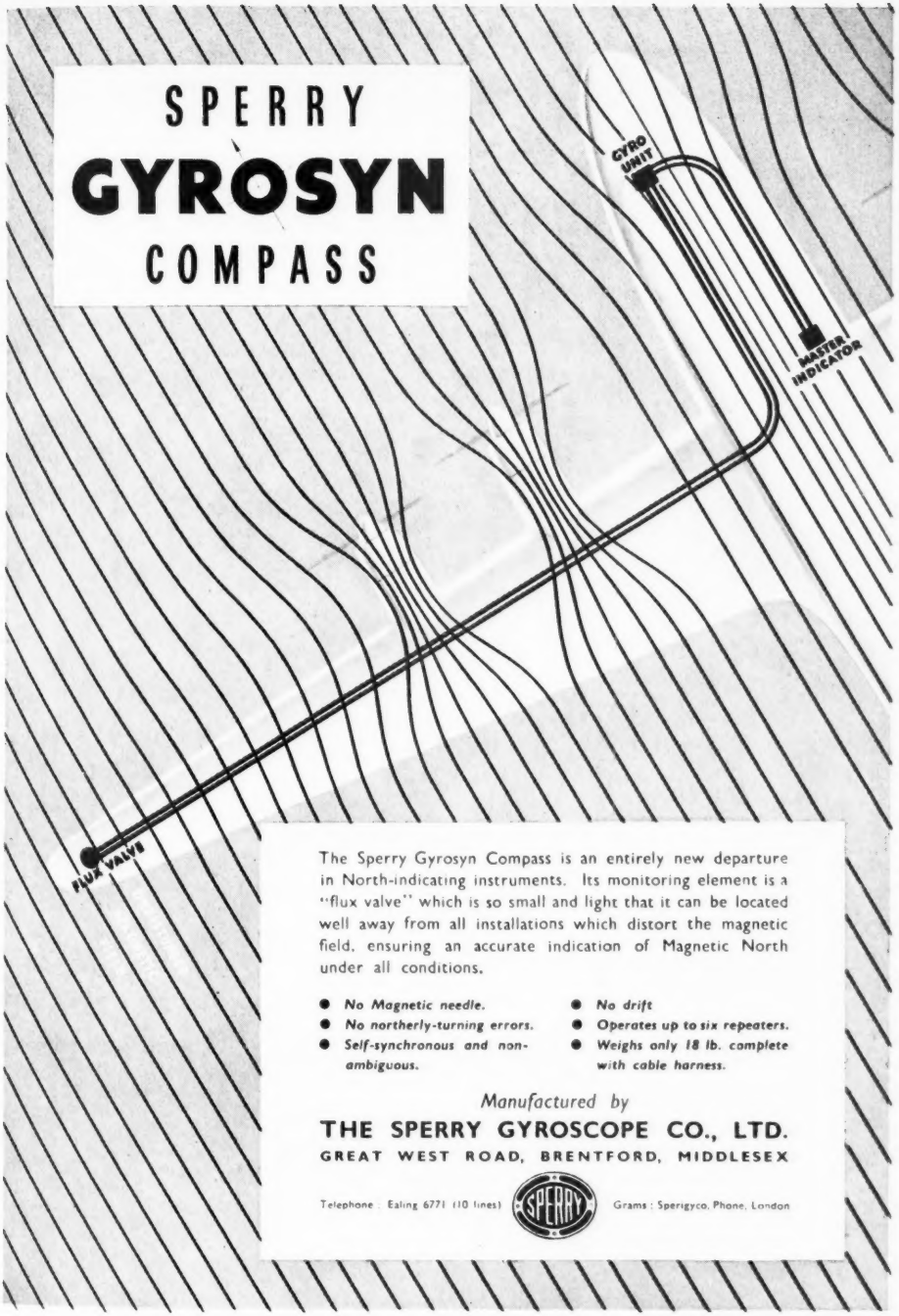

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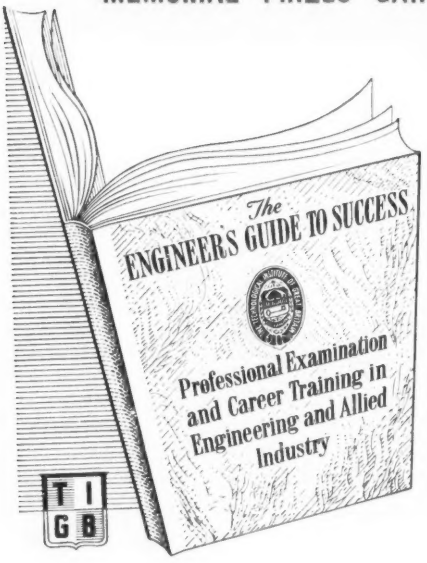

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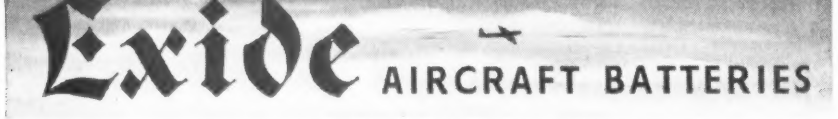

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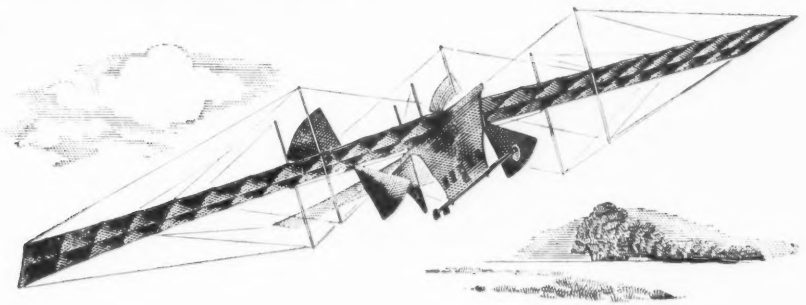

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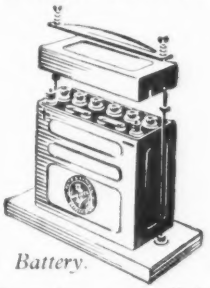

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Papers must be in English, in the third person, and typed on one side of the paper only, with double spacing and wide margins. When submitted they must be in their *final form for publication.* Only typographical errors may be corrected in proofs. Titles of papers should be brief.

Where practicable, a summary of not more than 250 words should be given at the beginning of the paper, giving its scope and conclusions.

All references should be numbered in the text where they occur, and the complete list of references given at the end of the manuscript. These references will be published at the end of the text. Footnotes should be numbered consecutively. Tables should be kept as concise as possible.

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Only very simple symbols and formulas should be typewritten. All others should be written carefully by hand in ink. Ample space for marking should be allowed above and below all equations. Greek letters used in formulas should be designated by name in the margin.

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Complicated exponents and subscripts should be avoided. Any complicated expression that recurs frequently should be represented by a special symbol.

Unless an abbreviation is one recognised as standard practice, both in this and other English-speaking countries, for example, b.h.p. for brake horse power, the meaning should be given in full on its first use.

THE ROYAL AERONAUTICAL SOCIETY

35th WILBUR WRIGHT MEMORIAL LECTURE

THE DEVELOPMENT OF ALL-WING AIRCRAFT

by

JOHN K. NORTHROP

Mr. Northrop is President and Chief Designer of Northrop Aircraft Inc. He has been designing and experimenting with the all-wing type of aeroplane since 1923 *and built his first machine in* 1928.

THE THIRTY-FIFTH Wilbur Wright Memorial Lecture was delivered before the Society by Mr. John K. Northrop on Thursday 29th May 1947 at 6 p.m. in the Lecture Hall of the Institution of Civil Engineers, Great George Street, S.W.1. The chair was taken by Sir Frederick Handley Page, C.B.E., President of the Society.

The President: They had now reached the highlight of the 1946-47 session, the Wilbur Wright Memorial Lecture. It seemed incredible to think that these memorial lectures had been going on for 35 years, no sooner was one over than another one came round. The Lecture was usually given in alternate years by an Englishman and an American, and this year they were fortunate in having as their lecturer that distinguished American, Mr. John K. Northrop.

Before introducing Mr. Northrop he had another duty to perform. As was customary on the occasion of the Wilbur Wright Memorial Lecture, as President, he had cabled Orville Wright as follows:—

"On May 29th 1947 your distinguished countryman John K. Northrop will read the 35th Wilbur Wright Memorial Lecture on The Development of All-Wing Aircraft. The reading of this annual lecture is a constant reminder of those early years of this century when you and your brother laid down so clearly, yet so simply, the firm foundations of the art of flying upon which must ultimately be built that structure for world peace which can never be destroyed."

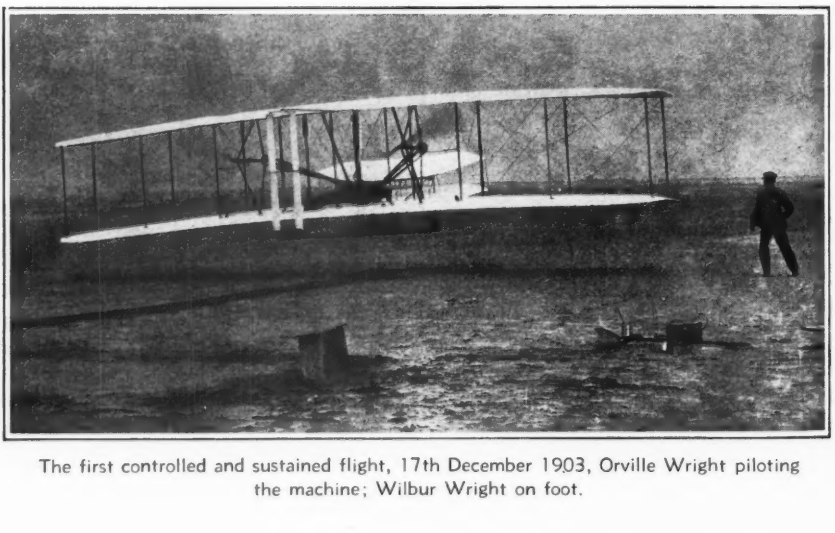
He had received the following reply:—

" Heartiest greetings to the Society and to all assembled to hear my esteemed fellow countryman Northrop deliver the 35th Wilbur Wright Lecture. I believe Mr. Northrop will bring to you a good message on matters useful in peace.

ORVILLE WRIGHT."

He had also sent the following cablegram to the Institute of the Aeronautical Sciences:

" On behalf of the Council and Members of the Royal Aeronautical Society I send you our greetings on the occasion of the reading of the 35th Wilbur Wright Memorial Lecture by your distinguished member John K. Northrop on The Development of All-Wing Aircraft."



The first controlled and sustained flight, 17th December 1903, Orville Wright piloting the machine; Wilbur Wright on foot.

They had cabled in reply:—

" On the occasion of the reading of the Wilbur Wright Memorial Lecture by our distinguished American contemporary John Northrop the Officers and Council of the Institute of the Aeronautical Sciences extend heartiest greetings to the Royal Aeronautical Society. We are all looking forward to a period of greater collaboration between the Societies on either side of the Atlantic.

P. R. BASSETT, President."

He now had great pleasure in introducing Mr. John K. Northrop. Mr. Northrop was well-known on both sides of the Atlantic for his work on all-wing aircraft. Indeed, he was one of the great pioneers in that field and probably knew more about this particular type of aeroplane than anyone. He was chief designer, President and everything else—in fact, he was the Northrop Aviation Company. He had been designing and developing the all-wing type since about 1923. This evening they were to have the pleasure and privilege of hearing from Mr. Northrop something of the difficulties and successes connected with that development.

He had pleasure in calling on Mr. Northrop to deliver his lecture.

ONE cannot undertake the presentation of one of the long series of Wilbur Wright Memorial Lectures without a deep sense of appreciation of the tremendous contributions made by the illustrious group of scientists and engineers who have given such great distinction to this event. The happy precedent of inviting individuals from without the United Kingdom to make this presentation in alternate years has gone far in the past toward improving the understanding, cooperative effort and fellowship of the English-speaking peoples, and I am deeply honoured to have been among those chosen to further this very worthy cause.

INTRODUCTION.

In choosing the title, "The Development of All-Wing Aircraft," as the subject of my lecture I run some risk of being accused of writing a company history rather than a paper of the broad scope ordinarily presented before this time-honoured institution. This is far from my intent, but being sincerely convinced that the all-wing aeroplane is a valuable step in the development of aeronautics, and desiring to contribute a maximum amount to the available data in the limited time at my disposal, my paper must be confined largely to experience gained by our company in its work on this subject.

Outside the efforts of the Horten Brothers in Germany there has, until a comparatively recent time, been little physical accomplishment in the development of the all-wing aeroplane except by our company. The contemporary Horten development has been fully described in technical reports emanating from Germany since the close of the European war. In many instances the Horten conclusions were surprisingly similar to our own. Their work was not carried so far, however, and I doubt that they had the sympathetic and responsible governmental backing and the resultant opportunities for development accorded us.

In considering the development of all-wing aircraft I would like first to distinguish between all-wing and tailless aeroplanes. Most tailless aeroplanes are not all-wing by our definition. There is a tremendous background of development in tailless types, which has been fully reported by Mr. A. R. Weyl in *Aircraft Engineering*. These articles outlined a surprising number of reasons for building tailless aircraft which have motivated the various designers and constructors over the years. Only one of the many advantages to be gained through such development has inspired our work, namely improved efficiency of the aeroplane.

More recently, through the rapid develop-

ment of turbo-jet power plants, a second advantage has arisen, which is the elimination of design difficulties attendant upon the impinging of high speed high-temperature jets on tail surfaces. Still more recently a third possible advantage has appeared, this being the (as yet unproved) probability that problems of stability in the transonic and supersonic ranges may be somewhat more simple of solution in the tailless type than in the older and more conventional arrangements.

Only the first of these basic advantages, namely that of improved efficiency, has been readily apparent over a number of years and, as a result, virtually all our efforts have been directed toward the reduction of parasite drag and the improvement of the ratio of the maximum trimmed lift coefficient ($C_{L_{max}}$) to the minimum drag coefficient ($C_{D_{min}}$). It is natural, then that we were not interested particularly in tailless aeroplanes as such; if we could not eliminate vertical tail surfaces, fuselages, and a substantial portion of interference drag, the gains to be made seemed not worth the effort necessary for their accomplishment.

Our work, therefore, through the years has been directed solely to all-wing aircraft, by which I mean a type of aeroplane in which all of the functions of a satisfactory flying machine are disposed and accommodated within the outline of the aerofoil itself. Of course, we have not as yet built any pure all-wing aircraft. All have had some excrescences, such as propellers, propeller drive shaft housings, jet nozzles, gun turrets and the like. We have, however, built a number of aeroplanes in which the minimum parasite drag coefficient has been reduced to approximately half that ordinarily attained in the best conventional aircraft of like size and purpose, and in some of the designs completed and tested the excrescences and variations from the aerofoil contour have been responsible for less than 20 per cent. of the minimum aeroplane drag.

BASIC ASSUMPTIONS.

A surprisingly large number of people, both within and without the aircraft industry, still appear to question the economic reasons for going to all the trouble to build an all-wing aeroplane. "Sure," they say, "after a lot of practice people can learn to walk on their hands, but it's most uncomfortable and unnatural, so why do it when nothing is gained thereby?" Actually, there are startling gains to be made in the aerodynamic and structural efficiency of an all-wing type, provided that certain basic requirements can be fulfilled by the type under question. These requirements can be simply stated as follows:

First, the aeroplane must be large enough so that the all-wing principle can be fully utilised. This is a matter closely related to the density of the elements comprising the weight empty and the useful load to be carried within the wing. The dimensions of the average human body may also at times be the limiting factor but, ordinarily, in the larger types of transport or bombardment aircraft in which we are most interested, it will be found that excessive sizes are not necessary in order to secure, within a wing of reasonable thickness ratio, adequate volume for a commercial cargo or bomb load plus the necessary fuel.

The extremes explored and satisfactorily flown to date in our experience range from a "buzz" bomb having a span of 29 feet, in which the warhead was cast as a portion of the aerofoil, to the 172-foot XB-35 long-range bomber aeroplane. These two aircraft are shown to scale in Fig. 1. The buzz bomb was practical because of the comparatively high specific gravity of the warhead, plus the fact that the configuration permitted almost all of the wing to be used as a fuel tank. The XB-35, on the other hand, is considerably larger than would be necessary to provide ample space for passenger and crew comfort and ample volume for payload, be it cargo or bombs. It was designed larger than necessary because we desired to keep the wing loading

Fig. 1.
The Northrop "Buzz" bomb and the XB-35 shown to scale.

comparatively low in this first large experimental venture. It has a normal gross weight of 165,000 lb., an overload gross weight of 221,300 lb., and sufficient volume within the wing envelope so that the maximum gross weight at take-off might well be increased to over 300,000 lb., somewhat over half of which could be devoted to bombs, fuel and miscellaneous payload. It may be seen, therefore, that there is a practical range of size within which the all-wing aeroplane can be used. If the requirements of space and volume do not permit the full use of the all-wing principle, a rudimentary nacelle may be added without losing its economic advantages.

The second basic requirement is that the all-wing aeroplane be designed to have sufficient stability and controllability for practical operation as a military or commercial aeroplane. We believe this requirement has been fully met by hundreds of flights completed with this type, and we are fully convinced of its practicability after having built a dozen different aeroplanes embodying scores of different configurations incorporating the all-wing principle.

In comparing all-wing and conventional types, we may fairly assume that spans of comparative aircraft having the same gross weight are equal, and as a further simplification we may for the moment neglect compressibility effects in our comparison of the advantages of all-wing and conventional types of large bombardment or transport aircraft having maximum velocities up to approximately 500 m.p.h.

COMPARISON OF MINIMUM DRAG AND MAXIMUM TRIMMED LIFT.

Based on these assumptions and on the following proved data on the all-wing type, a comparatively simple analysis of advantages may be made.

The ratio of the minimum parasite drag coefficient ($C_{D_{min}}$) for all-wing aeroplanes to that for conventional types is approximately 1:2. Minimum drag coefficients for a number of large bomber and transport aircraft such as the B-29, B-24, C-54 and others average approximately .023. The minimum drag coefficients for several all-wing types have been measured both in model and full-scale configurations and vary from less than .010 to about .0113, which is the figure for the XB-35 including armament protuberances, drive shaft housings, rudimentary nacelle for gun emplacements, and so on.

The ratio of maximum trimmed lift coefficient ($C_{L_{max}}$) for all-wing to conventional types is approximately 1.5:2.3. The latter figure is typical for a number of the large aeroplanes of conventional arrangement previously mentioned. The former is readily attainable in a configuration such as that of the XB-35 and may be subject to considerable improvement through the use of several types of high-lift devices yet to be proved.

For comparative aeroplanes of the same span and gross weight the selection of the required wing area will depend either on flight conditions, including take-off without flaps, or landing conditions. If the flight conditions govern, the ratio of required wing areas of all-wing to conventional aircraft will be 1:1 because the two wings are equally effective except under conditions of maximum lift. If landing conditions govern, the ratio will be $\frac{2.3}{1.5}$: 1, assuming the same landing speed in each case. If take-off with partial flap deflection governs, the ratio will be somewhere between the above two figures.

In large all-wing bombers and transports, and to a growing extent in conventional long-range transports as well, the ratio of gross weight at take-off to landing weight will approach 2:1. Therefore flight conditions are likely to govern the selection of wing area more than landing conditions. In the following calculations both extremes are used as indicative of the range of advantage to be gained by the use of the all-wing configuration. Referring to Fig. 2, it may be seen from equation (1) that the total minimum parasite drag of the all-wing aeroplane in terms of the conventional aeroplane will vary from 50 per cent. if flight conditions govern, to 77 per cent. if landing conditions govern. In this equation $(D_p)_a$ and $(D_p)_c$ represent the parasite drags of all-wing and conventional aeroplanes while S_a and S_c represent the respective wing areas.

It is a well-known fact, based on the Breguet range formula, that with conventional reciprocating engines and propellers the speed for maximum range is approximately that at which parasite drag and induced drag are equal. Therefore, at the same cruising speed as the conventional aeroplane the all-wing type will require from 25 per cent. to 11½ per cent. less power, as shown in equation (2), and with the same amount of fuel will fly from 33 per cent. to 13 per cent. farther, as indicated by equation (3). In these equations P represents power required, and D total drag. V is aeroplane velocity and R range, with the suffices a and c again denoting the all-wing and conventional con-

1. $$\frac{(D_p)_a}{(D_p)_c} = .50 \times \frac{S_a}{S_c}$$
$$= .50 \times 1.0 = .50 \text{ (flight condition)}$$
$$= .50 \times \frac{2.3}{1.5} = .77 \text{ (landing condition)}$$

2. $$\frac{P_a}{P_c} = \frac{D_a}{D_c} \times \frac{V_a}{V_c} = \frac{D_a}{D_c} \text{ (at equal speeds)}$$
$$D_a = (D_i)_c + (.50 \text{ to } .77) \times (D_p)_c$$
$$= (1.5 \text{ to } 1.77) \times (D_i)_c$$
$$D_c = 2(D_i)_c$$
$$\text{Therefore } \frac{P_a}{P_c} = \frac{1.5}{2} \text{ to } \frac{1.77}{2} = 75\% \text{ to } 88.5\%$$

3. $$\frac{R_a}{R_c} = \frac{P_c}{P_a} = \frac{1}{.75} \text{ to } \frac{1}{.885} = 133\% \text{ to } 113\%$$

Fig. 2.

figurations. If the all-wing aeroplane is operated at *its* most economical speed, instead of the most economical speed of the conventional aeroplane, it will fly 19 per cent. to 7 per cent. faster and the range will be from 41 per cent. to 14 per cent. greater with the same amount of fuel, as indicated in equation (4) of Fig. 3.

for best fuel economy, the advantages of the all-wing configuration, when used in combination with these power plants, will closely approach the above figures for maximum range as well as high speed.

These advantages are summarised graphically in Fig. 4 and are all based on the simple aerodynamic values obtained with all-wing

4. $$\frac{R_a}{R_c} = \sqrt{\frac{(C_{Dp}S)_c}{(C_{Dp}S)_a}} = \sqrt{\frac{1.0}{.5}} \text{ to } \sqrt{\frac{1.0}{.77}} = 1.41 \text{ to } 1.14$$

and

$$\frac{V_a}{V_c} = \sqrt[4]{\frac{(C_{Dp}S)_c}{(C_{Dp}S)_a}} = \sqrt[4]{\frac{1.0}{.5}} \text{ to } \sqrt[4]{\frac{1.0}{.77}} = 1.19 \text{ to } 1.07$$

5. $$\frac{P_a}{P_c} = \frac{D_a}{D_c} \text{ (at equal speeds)}$$

$$D_a = (D_i)_c + (.50 \text{ to } .77) \times (D_p)_c$$
$$= (D_i)_c + (.50 \text{ to } .77) \times (D_i)_c \times 4$$

and $$D_c = (D_i)_c + (D_i)_c \times 4$$

$$\text{Therefore } \frac{P_a}{P_c} = \frac{1 + (2 \text{ to } 3.08)}{1 + 4} = 60\% \text{ to } 81\tfrac{1}{2}\%$$

6. $$\frac{R_a}{R_c} = \frac{P_c}{P_a} = \frac{1.0}{.60} \text{ to } \frac{1.0}{.815} = 166\% \text{ to } 122\%$$

Fig. 3.

ADVANTAGES OF LOW PARASITE DRAG.

Under high-speed conditions with any type of power plant the parasite drag becomes a much larger percentage of the total drag than for cruising conditions with reciprocating engines. At high speed the parasite drag may account for 80 per cent. or more of the total, while the induced drag drops to 20 per cent. or less. Using an assumed figure of 80 per cent. parasite drag, which is probably correct to ± 10 per cent. for most aircraft, the power required to drive the all-wing aeroplane at the same speed as the conventional aeroplane will be from 40 per cent. to 18½ per cent. less, as shown in equation (5), and the range, at the high speed of the conventional aeroplane, will be from 66 per cent. to 22 per cent. greater, as indicated in equation (6). As turbo-jet and turbo-prop power plants both operate at relatively high speed

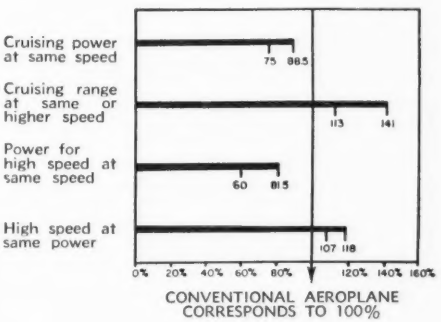


Fig. 4.
Graph of performance characteristics of all-wing aeroplane.

aeroplanes; namely, that $C_{D_{min}}$ equals 50 per cent. of conventional; $C_{L\ max}$ equals 65 per cent. of conventional. The probabilities are that the minimum parasite drag can, within a comparatively short time, be reduced, at least for commercial types, to about 40 per

cent. of the conventional figure and that the maximum trimmed lift coefficient ($C_{L_{max}}$) may, within a similar short time, be increased to at least 75 per cent. of conventional values.

METHODS FOR INCREASING MAXIMUM TRIMMED LIFT.

One of the most interesting devices for increasing maximum lift is, of course, the judicious use of boundary layer control in conjunction with turbo-jets or gas turbines. Another involves the development of a better combination of low pitching moment flaps and trimming devices which will permit of "lifting ourselves by our boot straps" in a more successful manner than we have achieved to date. Model configurations tested up to this time, employing such methods, have shown improvements of .1 or .2 C_L' over the figure now used of 1.5.

A third possibility of rather unconventional nature remains to be proved in the all-wing aeroplane. This consists of placing the C.G. behind the aerodynamic centre of the wing, eliminating inherent longitudinal stability by so doing and replacing this characteristic, which heretofore we have always considered as an essential to satisfactory aircraft design, by highly reliable (and perhaps duplicate) automatic pilots which take over the function of stability from the airframe and may perhaps do a better job of maintaining the proper attitude than the present classical method. While unconventional and possibly a bit horrifying to those unaccustomed to the idea, it may have practical application to very large aircraft where the pilot's skill and strength are largely supplanted by mechanical means of one sort or another, and wherein the pilot controls the mechanism which in turn places the aeroplane at the desired attitude. If the C.G. is located aft of the aerodynamic centre the aeroplane will trim at a high angle of attack with the flaps or elevator surfaces deflected downward rather than upward from their normal position, thereby increasing the camber and rendering the whole aerofoil surface a high-lift device. It is possible that trimmed lift coefficients in the order of 2.0 may be achieved by this method, and experiments completed to date with such a device on conventional aircraft show that the C.G. may be displaced at least 10 per cent. of the mean aerodynamic chord aft of a normal position without any uncomfortable results in the flying characteristics of the aeroplane.

When these improvements in $C_{L_{max}}$ and $C_{D_{min}}$ can be realised, further startling gains in performance will accrue, as will be outlined later. It would seem, however, that the present accomplishments offer sufficient incentive to warrant all they have cost in time, effort and money, and that the question, "why bother with an all-wing aeroplane?" is already well answered.

OTHER MAJOR ADVANTAGES.

There are other major advantages of the all-wing type which cannot be so definitely evaluated but which can and do contribute appreciably to improvement in efficiency and range. Two of these, namely the elimination of jet-tail surface interference, and the possible elimination of wing-tail surface shock wave interference, have already been mentioned. The third, and the most immediately applicable to designs of the near future, is the improved adaptability of all-wing types to the distribution of major items of weight empty and useful load over the span of the wing. While such distribution can be made to a limited extent in conventional aeroplanes, it can be much more fully accomplished in the all-wing type. Such weight distribution results in substantial saving in structural weight which have important effects on the ratio of gross weight at take-off to landing weight. An analysis of the range formula indicates that this ratio is one of the most important range parameters. Competent authority has shown that distribution of fuel in the wings instead of the fuselage of a large conventional modern

transport would allow an increase in gross weight of 16 per cent. without increase to weight empty, with a corresponding increase in range up to 30 per cent.

It is fairly obvious that the all-wing aeroplane provides comparative structural simplicity, plus the possibility of structural material distribution in a most effective way at maximum distances from the neutral axis, plus an opportunity to stow power plant, fuel and payload at desirable intervals along the span of the wing, which cannot be equalled in conventional types. These matters are rather intangible and difficult to illustrate by numerical relationships. They depend to a large extent on the type and size of the aeroplane, what it is designed to carry, and what the desired high speed may be.

PROBLEMS INVOLVED IN ALL-WING DESIGN.

Having demonstrated, perhaps, that the advantages of the all-wing type are fully worth striving for, let us consider the problems involved and their solution. Based on our present experience these difficulties do not appear now of surpassing magnitude, but in 1939 several of them seemed so serious as to discourage the most hardy optimist.

To one testing a swept-back aerofoil having a desirable root thickness, taper ratio and symmetrical section, together with reasonable washout at the tips such as might be designed from the then available data, the first results were a bit terrifying. Fig 5 shows the pitching moment curves obtained from the first wind tunnel tests of a model built to the above description. It may be seen that the elevator effect is erratic, changes in sign with varying deflections, and would be entirely unsuitable for the control of an aeroplane. It may also be seen that the degree of static longitudinal stability indicated by the average slope of the pitching moment curves is less than that considered desirable in a conventional aeroplane. Experiments involving visual observation of tufts on the model indicated a

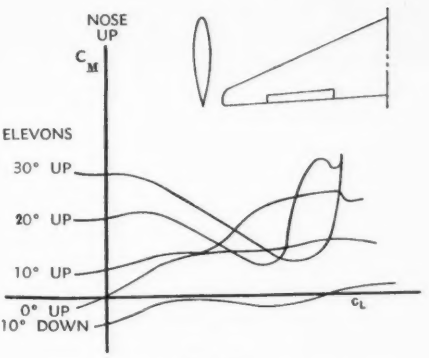


Fig. 5.
Elevon effectiveness without trailing edge extension.

separation along the trailing edge of the aerofoil which was apparently due to the planform configuration, and which was responsible for the erratic curves. In early experiments a simple addition of 10 per cent. to the chord length with a straight line contour from approximately the 70 per cent. chord point to the new 110 per cent. chord point, almost completely eliminated the difficulty and pitching moment curves for the revised model are shown in Fig. 6.

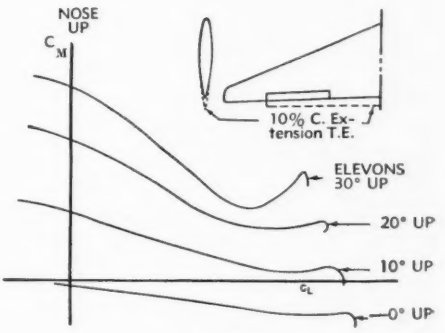


Fig. 6.
Elevon effectiveness with trailing edge extension.

N1M, FIRST FULL-SCALE AEROPLANE

It was soon determined that data applicable to conventional wings with little or no sweep were completely unreliable for the

degree of sweepback required in practical all-wing designs, and that a whole new technique had to be developed to determine the limits within which taper ratio, sweepback and thickness ratio could be combined for satisfactory results. All these variables were explored in a series of wind tunnel models, and when a reasonably satisfactory group of configurations had been determined it was decided to build our first piloted flying wing, the N1M (Northrop Model 1 Mockup).

Because of the many erratic answers and unpredictable flow patterns which seemed to be associated with the use of sweepback, it was decided to try to explore most of these variables full scale, and the N1M provided for changes in planform, sweepback, dihedral, tip configuration, C.G. location, and control-surface arrangement. Most of these adjustments were made on the ground between flights; some, such as C.G. location, were undertaken by the shift of ballast during flight. The variations to which this first aeroplane was subjected are indicated in Fig. 7, which shows two extremes of arrangement in which the aeroplane was found to be quite satisfactory in flight.

It is an interesting commentary on the comparative ease with which the basic problems of controlled flight were solved to note that no serious difficulties were experienced in any flight attempt, or with any of the various configurations used. Some "felt" better to the pilot than others, but at no time was the aeroplane uncontrollable or unduly difficult to fly. The principal early troubles

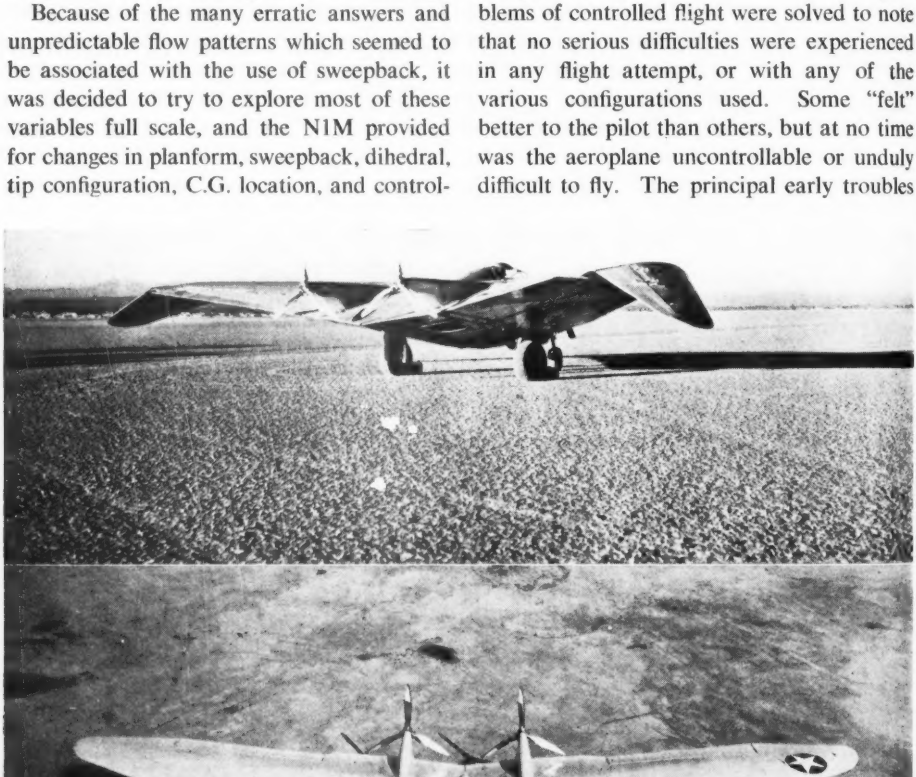


Fig. 7.
Variations on the Northrop N1M.

were related to the cooling of the small "pancake"-type air-cooled engines which were buried completely within the wing, and because of the pusher arrangement did not have the benefit of slipstream cooling in taxi-ing, take-off and climb. Engine-cooling problems seriously handicapped the early flights but later, somewhat larger engines were installed and the design of the cooling baffles was sufficiently improved so that repetitive sustained flights were accomplished easily.

The first flight was more or less an accident in that, while taxi-ing at comparatively high speed over the normally smooth surface of the dry desert lake bed used as a testing field, the pilot struck an uneven spot. He was bounced into the air and made a good controlled flight of several hundred yards before returning to earth. Altogether, this first aeroplane was used in over 200 flights of substantial duration, during which numerous configurations were tested and a great deal of work was done in the determination of the best types of control surface and surface control mechanism.

ELEVONS AND RUDDERS.

From the inception of the work, longitudinal and lateral controls were combined in the "elevon," which word was coined to designate the trailing edge control surface members which operate together for pitch control and differentially for roll control. At no time during early tests did control about the pitch or roll axes give any appreciable difficulty. The control which was least expected to cause difficulty gave the most, namely the rudder.

Early in the test programme it was found that the aeroplane had quite satisfactory two-control characteristics that is, a normal turn resulted from a normal bank without the use of rudder controls and as a result, throughout the programme we have often considered the elimination of rudder controls entirely. It was indeed fortunate that the first aeroplane developed such docile characteristics, for many of the rudder configurations tried proved to be ineffective—or worse, affected the flight characteristics of the aeroplane adversely.

From the start it was determined to eliminate to the greatest extent possible, vertical fin and rudder surfaces; first, because they violated the all-wing principle and added drag to the basic aerofoil; second, because with the moderate sweepback employed in our early designs the moment arm of a conventional rudder about the C.G. was small, and an excessively large vertical surface would have resulted had we tried to achieve conventional yaw control moments. The rudder development was therefore concentrated on finding a type of drag-producing device at the wing tips which would give adequate yawing forces without affecting pitch or roll. To this end we tried 25 or 30 different configurations in flight which were first tested in the wind tunnel. As a result of this experience it was concluded that dynamic reactions were likely to be very different from static reactions; some of the configurations which looked best in the wind tunnel proved to be quite unsatisfactory in flight.

The best and most practical rudder found was one of the simplest in concept and one of the first to be flown, namely a plain split flap at the wing tip which could be opened to produce the desired drag. This flap was later combined with the trimming surface needed to counteract the diving moment of the landing flaps, forming the movable control surfaces at the wing tip of the XB-35, as shown in Fig. 8.

Among the many flights accomplished with the first experimental aeroplane were several in tow of other aircraft where the distance to be covered, or the altitude to be gained, made it impractical to depend solely on the aeroplane's own engines. After a few minutes of acquaintanceship with the slight differences brought about by the presence of the tow cable, the aeroplane behaved well in

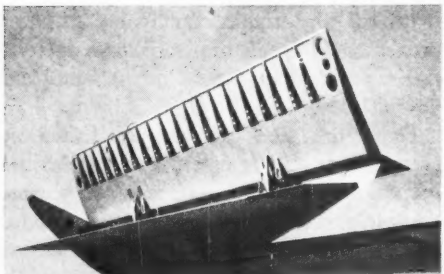


Fig. 8.
Movable control surfaces at the wing-tip of the XB-35.

tow and several comparatively high altitude flights were made to investigate the spin characteristics. These appeared to be quite normal, based on preliminary tests of this aeroplane. Later experience, however, indicated that the spin characteristics of tailless types vary from one design to another, in the same fashion as may be expected in conventional types, and that no broad generalisation as to spin behaviour can be made with safety.

N9M, FLYING MOCKUP FOR BOMBER.

The N1M was first flown in July of 1940 and about a year was consumed in a combination of aerodynamic tests and attempts to solve engine cooling problems. As soon as good sustained flight demonstrations could be made on schedule the Army Air Forces took active interest in the programme and top-flight officers, including General H. H. Arnold and Major General Oliver P. Echols, encouraged us to investigate the application of the all-wing principle to large bomber aircraft. To this end it was decided to construct four scale models of a larger aeroplane. These were designated N9M (Northrop Model 9 Mockup) and they duplicated, except for the power plant and propeller arrangement, the aerodynamic configuration of the proposed XB-35 aeroplane. This design is shown in Fig. 9.

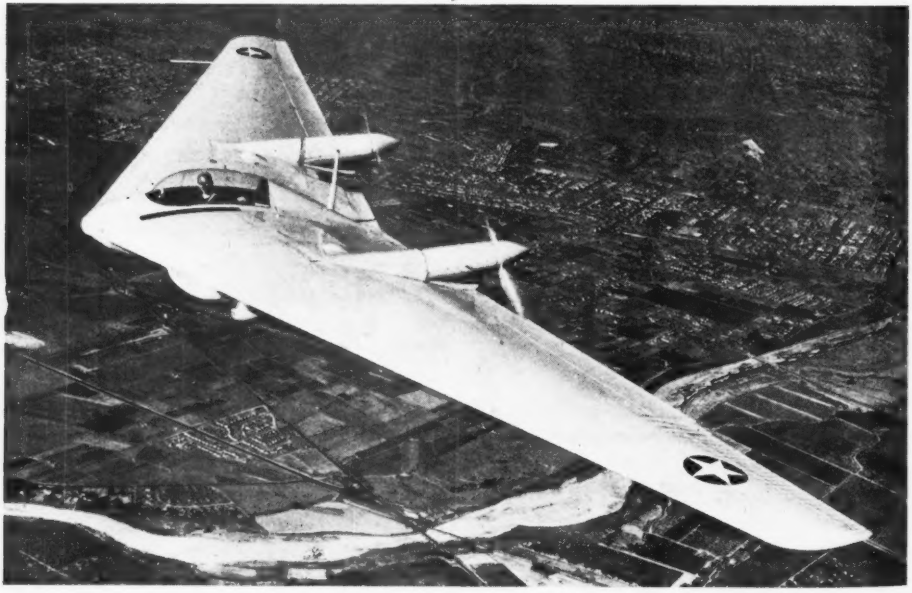


Fig. 9.
A Northrop N9M scale model.

The first of these aircraft was completed and test flown on December 27, 1942, and had completed about 30 hours of test flying with pilot (and sometimes an observer) when it crashed, killing the pilot. The machine had been on a routine test flight across the desert away from its base, and was out of sight of technically qualified observers at the time of the accident. However, all evidence pointed to a spin, and the attitude of the aeroplane on the ground indisputably indicated auto-rotation at the time of impact.

This loss was a serious setback and work was started immediately to recheck the spin characteristics of the aeroplane in a spin tunnel. It was later determined, both in the tunnel and in flight, that recovery was good, although a bit unconventional (requiring aileron rather than elevator action), but that the spin parachutes which had been attached to the aeroplane for the low-speed stalling and stability tests then in progress were ineffective as to size and improperly located.

SPINNING AND TUMBLING CHARACTERISTICS.

Subsequent models, over hundreds of flights, gave no trouble. The low-speed stall and spin tests with rear C.G. positions were accomplished without further difficulty and the N9M proved an invaluable test bed in which various control configurations could be proved in detail. A large number of additional rudder configurations were developed and tested on the N9Ms; likewise different types of mechanical and aero-dynamic boost for the control surfaces were investigated, as well as the general behaviour of the aeroplane in all types of air, and with different C.G. positions.

In connection with the model spin tests of this aeroplane, an investigation of the tumbling characteristics of the type was made in the spin tunnel. These tests showed that if the model was catapulted into the airstream with an imposed high velocity about the pitch axis in either direction, it would continue to tumble or come out of the manœuvre, depending on comparatively minor differences in elevon and C.G. position. In other words, under circumstances of induced rotation about the pitch axis the recovery was marginal. However, it would never tumble from any normal flight condition, such as a stall, spin, or any other to-be-expected manœuvre. In some configurations, if dropped vertically trailing edge down into the wind stream, a tumbling action would be induced which might or might not damp out. This was not judged a serious matter in view of the fact that a vertical tail slide is hardly a manœuvre to be courted, even by a fighter aeroplane, let alone a 100-ton bomber.

The three remaining N9Ms have been flown almost continuously since their completion dates to the present. Only recently have all desirable test programmes been completed and the aeroplanes relegated to a semi-retired status from which they are withdrawn only for the benefit of curious pilots.

XP-79, ROCKET-POWERED AEROPLANE.

In September of 1942 we conceived the idea of combining the newly developed liquid-rocket motors with a flying wing in a high speed and highly manœuvrable fighter. The physical dimensions of the human frame immediately became a limiting size factor and for this reason, as well as because much higher accelerations can be withstood for longer periods in the prone position, it was decided to place the pilot prone in this design. Three experimental, full-size glider versions of this little aeroplane were rapidly completed and a long series of glider tests undertaken. In order to achieve the utmost in low drag and light weight, the original aeroplanes were mounted on skids and the first glider tests were attempted with an automobile tow. Because of the rugged construction of the gliders they had a fairly heavy wing loading and the equipment provided for towing

Fig. 10.
A glider version of the XP-79 with detachable dollies for take-off.

proved to be incapable of achieving enough speed for take-off.

As a second expedient, detachable dollies were built from which the aeroplane was expected to take off at flight speeds. Fig. 10 shows this arrangement. Minor crack-ups occured with this configuration and it was finally decided to compromise the aerodynamic cleanness of these first test aeroplanes in order to provide a rugged permanent and dependable landing gear for experimental purposes, as shown in Fig. 11. The unusually large fin used here was required to stabilise the fixed landing gear, a substantial portion of which extended ahead of the C.G. After this gear was installed, and with another aeroplane as the towing medium, the take-off difficulties were eliminated and a number of successful glider flights were made.

These aeroplanes were flown both with and without wing-tip slots and slats which were tested for the purpose of eliminating tip-stall difficulties, as will be described later. They were also flown with a wide variation in vertical fin area, to determine the amount

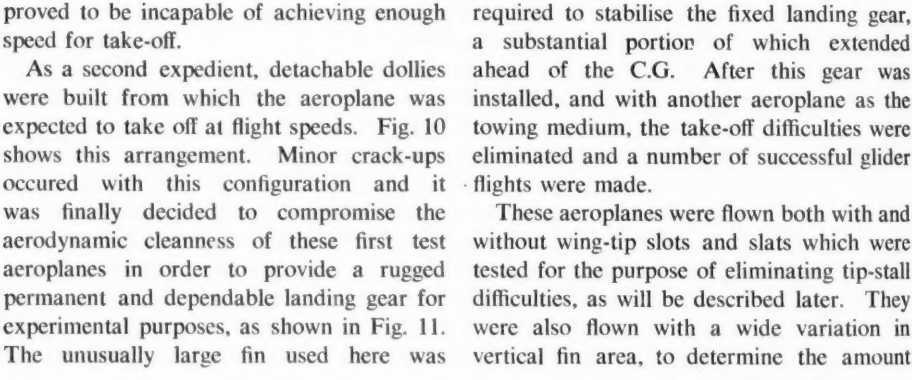


Fig. 11.
Experimental version of the XP-79 with fixed landing gear shown during one of the early rocket-powered flights.

necessary or desirable for various flight conditions.

In one memorable test during which the aeroplane was equipped with a fixed slat, a rather peculiar accident occurred. The pilot, as mentioned before, lay prone within the wing contour. Two escape hatches were located approximately opposite the centre of his body, one on the upper surface, the other on the lower surface. The handle which released the escape hatches was located close to the handle which released the towing cable from the tug aeroplane. At the start of this particular flight, after a successful climb to 10,000 ft., the pilot inadvertently released the escape hatches at the time of his release from tow, and as a result partially fell out of the aeroplane. The instinctive grasp on the control mechanism resulted in an indescribable wing-over manœuvre. When things calmed down the pilot found himself in a steady, uniform glide with the aeroplane upside down. Minor movement of the controls seemed to produce little effect and the much-shaken individual crawled out of the aeroplane, sat on the leading edge of the centre section while he checked his parachute harness, and then slid off to make a perfectly normal parachute descent. The aeroplane, undisturbed by the change in C.G., continued a long circling flight of the test area and finally landed in a normal continuation of its upside down glide, a short distance from the take-off point. It was rather seriously damaged but not so much so as to prevent repair. A later check in the wind tunnel indicated that there was a very stable region in inverted flight with this particular slat combination. Later the slats were abandoned as unnecessary and perhaps undesirable.

The airframe was considered suitable for the purpose intended long before the rocket motors had been developed to a degree of reliability considered safe for use, but finally a small motor having about five minutes' duration, was installed and a number of rocket-powered flights were accomplished. Fig. 11 shows the aeroplane during one of these tests. The first powered flight occurred in July of 1944.

Although the first concept of the XP-79, as this fighter was designated, was as a rocket-powered vehicle (similar in basic idea to the Messerschmitt ME-163), it soon became apparent that the completion of the rocket motors would be far behind schedule and that serious difficulties were attendant to this development. One of the basic concepts for the full-size motor was that the fuel pumps would be driven by rotation of the combustion chambers, which were set at a slight angle to the thrust axis in order to develop torque. It was not foreseen that the rotation of the combustion chambers would have a serious effect on the combustion therein, and this difficulty, never completely solved, caused the abandonment of the particular engine which was being developed for the project.

XP-79B TURBO-JET AEROPLANE.

As no alternative rocket engine was available, it became necessary to modify the design to incorporate turbo-jet power plants, and the second of the XP-79 series, called the XP-79B, shown in Fig. 12, was completed with two Westinghouse B-19 turbo-jets and first airborne on September 12, 1945. The take-off for this flight was normal, and for 15 minutes the aeroplane was flown in a beautiful demonstration. The pilot indicated mounting confidence by executing more and more manœuvres of a type that would not be expected unless he were thoroughly satisfied with the behaviour of the aeroplane.

After about 15 minutes of flying the aeroplane entered what appeared to be a normal slow roll, from which it did not recover. As the rotation about the longitudinal axis continued the nose gradually dropped, and at the time of impact the aeroplane appeared to be in a steep vertical spin. The pilot endeavoured to leave the aircraft but the speed was so high that he was unable to clear it

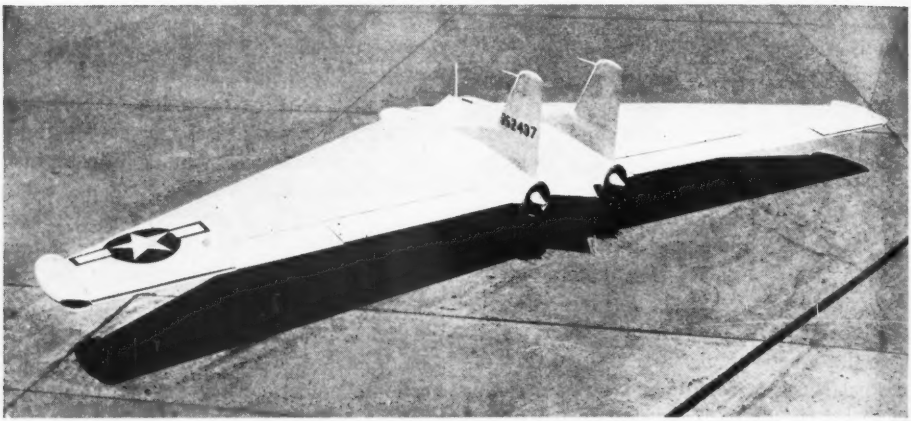


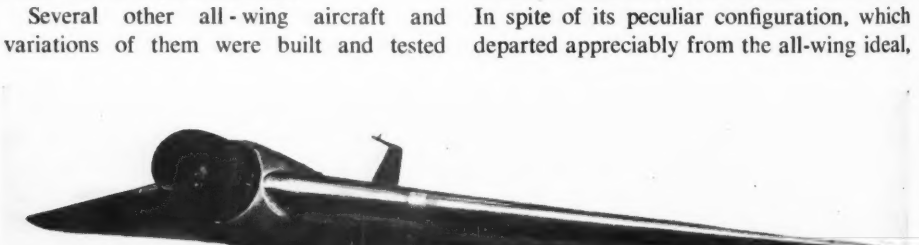
Fig. 12.
The Northrop XP-79B turbo-jet aeroplane.

successfully. Unfortunately, there was insufficient evidence to fully determine the cause of the disaster. However, in view of his prone position, a powerful, electrically-controlled trim tab had been installed in the lateral controls to relieve the pilot of excessive loads. It is believed that a deliberate slow roll may have been attempted (as the pilot had previously slow rolled and looped other flying-wing aircraft developed by the company) and that during this manœuvre something failed in the lateral controls in such a way that the pilot was overpowered by the electrical trim mechanism.

ALL-WING BUZZ BOMBS.

Several other all-wing aircraft and variations of them were built and tested during the same period. Shortly after the advent of the V-1 an all-wing "buzz" bomb was designed and built, the final configuration of this missile being shown in Fig. 13. This aeroplane housed the German V-1 resonator in a duct in the centre of the wing and carried twice the German warhead in cast wing sections on each side of the power plant with fuel in the outer wings. Several were built and flown successfully.

The first of these buzz bombs was tested as a pilot-controlled glider with good success. It was very small, as shown in Fig. 14, and incorporated a number of extra bumps which were originally conceived to be the best way to carry standard 2,000 lb. demolition bombs. In spite of its peculiar configuration, which departed appreciably from the all-wing ideal,



F.g 13.
The Northrop all-wing Buzz bomb.

Fig. 14.
The pilot-controlled glider model for the Buzz bomb.

it had quite good flight characteristics, was flown on a number of occasions (the aeroplane was successfully slow-rolled) and demonstrated the suitability of the type for the purpose intended.

The one difficulty experienced in this series of tests is worthy of note. The piloted version of the buzz bomb naturally required some type of landing gear for take-off and landing, and in this case we employed tiny, low-pressure air wheels, rigidly mounted in the airframe structure and extending only a few inches below the contour of the aerofoil or, more specifically, the bomb-shaped bumps thereon. Landing on this gear involved bringing the aeroplane in at an altitude of approximately 15 per cent. to 20 per cent. of the mean aerodynamic chord just prior to contact, and no amount of practice on the part of the pilot produced a technique satisfactory for this purpose. In every case a change in airflow appeared to develop as the aeroplane approached within a quarter-chord length of the ground. The drag was apparently reduced, the lift increased and the aeroplane rose, in spite of anything the pilot could do, to a height of 8 or 10 ft. above the ground, at which point it stalled and flopped down out of control. This manœuvre resulted in a number of rough landings but no damage to either the pilot or the aeroplane. It was later found that the only way to make any sort of smooth landing was to bring the aeroplane in at comparatively high speed and actually fly it on to the ground. This difficulty was not experienced in aeroplanes having normal landing height above the ground, such as the N9M and XB-35.

XB-35, LONG-RANGE BOMBER.

Duing all this development and testing of other types and scale versions of the XB-35, the design and construction of the big ship had been under way. N9M aeroplanes had proved the practicability of the design. They closely approached the XB-35 configuration with the exception that they mounted only two pusher engines, located at positions corresponding to points midway between engines 1 and 2, and engines 3 and 4.

The problem of control-surface actuation on the big bomber involved the development

Fig. 15.
The Northrop XB-35.

and testing of a complete hydraulic control system, as none of the aerodynamic boosts or balances developed and tested in the N9M models had proved satisfactory. The system used in the XB-35 employs small valves which are sensitive to comparatively minute movements of the control cable and which, when displaced, permit large quantities of oil to flow into the actuating cylinders. This arrangement eliminates any pilot "feel" of the load on the control surfaces unless a deliberate arrangement for force feedback is made. Rather than undertake this latter step, a comparatively simple force mechanism, which is sensitive to accelerations and airspeed, was developed. This device gives the pilot a synthetic feel of the aeroplane which can be adjusted in intensity to anything he likes, and which has proved satisfactory in flight. For reasons to be outlined shortly, a synthetic feel was much more satisfactory than the feedback of actual control-surface loads, particularly at high angles of attack.

The XB-35 was first flown from Northrop Field to the Muroc Army Test Base in June of 1946. The first several flights indicated no difficulties whatsoever with the airframe configuration. Indications of trouble with propeller governing mechanisms were discerned at an early date and it was shortly discovered that flights of any substantial duration could not be accomplished because of oil leakage in the hydraulic propeller governing system. On the last flight difficulty with both propellers on one side caused a landing with asymmetrical power, which was accomplished without trouble.

The next six months, from August to March, were spent in a vain attempt to eliminate these difficulties, plus those caused by a series of engine reduction gear failures. To date the XB-35 has not had sufficient time in the air to fully demonstrate its ability to meet its design performance guarantees. However, large-scale model tests in numerous tunnels have indicated the low-drag figures presented earlier in this paper, and preliminary speed versus power tests completed early this month have given gratifying confirmation of our original expectations. Flights accomplished to date have included all manœuvres necessary for large bombardment aeroplanes. So far, however, violent manœuvres have not been attempted and no exact evaluation of stability and control parameters has been possible. The appearance of the XB-35 in flight is shown in Fig. 15.

Two turbo-jet powered all-wing aeroplanes, having the same basic shape and size as the XB-35 are virtually complete at this time and will be flying late this summer. They are powered by eight jets having a sea level static thrust of 4,000 lb. apiece. They incorporate small vertical fins to provide the same aerodynamic effect as the propeller

shaft housings and propellers of the XB-35. Fig. 16 shows a model of this aeroplane.

Let us now turn to considerations of stability and control of the all-wing aeroplane. They are quite different from those of conventional types and, unless reasonably well understood, may lead to discouragement at an early date concerning projects well worth further evaluation.

STATIC LONGITUDINAL STABILITY.

In any aeroplane the primary parameter determining the static longitudinal stability is the position of the centre of gravity with respect to the centre of lift or the neutral point. Obviously, the neutral point may be shifted aft by adding a tail or by sweeping the wing, or the C.G. may be shifted forward by proper weight distribution, so that from the standpoint of static stability no particular configuration has any special advantage except as it affects the possibilities of proper balance. In an all-wing aeroplane the elimination of the tail makes the problem of balance somewhat more critical but not excessively so.

Unfortunately, for any given aeroplane the neutral point does not ordinarily remain fixed with variations of power, flap-setting or even lift coefficient, so that the aft C.G. limit for stability is often prescribed by some single flight condition. In our experience with tailless aircraft, the critical condition has always occurred for power-off flight at angles of attack approaching the stall.

CHARACTERISTICS AT HIGH LIFT.

The pitching instability of a swept wing at high lift coefficients is by now a somewhat familiar phenomenon. The complete mechanisms involved, however, are still somewhat obscure. There are apparently two opposing effects which are of prime importance. They are the tendency for sweepback to increase the relative tip loading and also (by creating a span-wise pressure gradient) to promote boundary layer flow toward the tip. On a plain swept-back wing the latter effect apparently nullifies the former, so that there occurs in the tip portion of the wing a gradual decrease in effective section lift-curve slope with a resulting progressive decrease

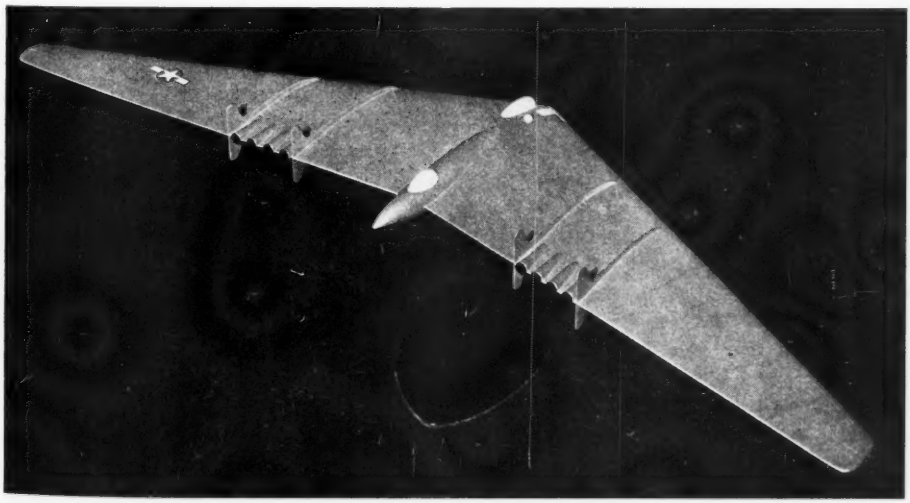


Fig. 16.
A model of a new turbo-jet all-wing aeroplane at present being developed by Northrop Aircraft

in stability. This effect is indicated in Fig. 17, which also shows that the tip, under these circumstances never completely stalls, as evidenced by the stable pitching moments occurring at the maximum lift coefficient. On the other hand, as illustrated in Fig. 18, the

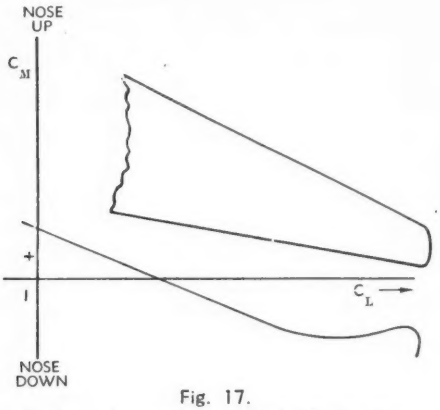


Fig. 17.
Pitching characteristics at high lift of a plain swept-back wing.

addition of end plates will prevent to a large extent the effects of span-wise flow, thereby straightening the pitching moment curve but producing the normally-expected tip stall, as evidenced by the strongly unstable moments in the vicinity of the maximum lift coefficient. Thus, any modification to the basic wing which affects the span-wise flow will have a noticeable effect on the pitching behaviour at high lift coefficients.

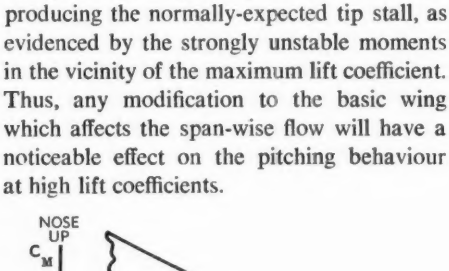


Fig. 18.
Pitching characteristics at high lift of a swept-back wing with end plates.

In the case of the XB-35 the propeller shaft housings act to inhibit span-wise flow and straighten out the moment curve below the stall as in the case of the end plate; but in order to obtain stability at the stall, a tip-slot is provided to increase the stalling angle of the tip sections. These effects are illustrated in Fig. 19, which also shows that by raising the trim flap in the outer 25 per cent. span and lowering the main flap in the inner 35 per cent. span, the stability characteristics are noticeably affected, presumably because of a decrease in span-wise pressure gradient and therefore in boundary layer flow.

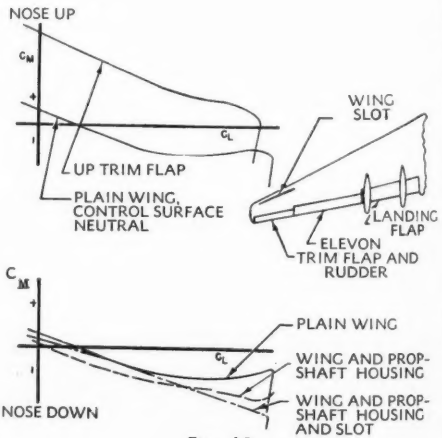


Fig. 19.
Effect of various devices and control surface deflection on XB-35.

Recent investigations have indicated that the problem of static longitudinal instability near the stall for plain swept-back wings depends not only on sweep but also on aspect ratio and it now appears that for a given sweepback the magnitude of the unstable break in the moment curve decreases with decreasing aspect ratio, eventually vanishing.

The possibility of controlling the stalled portions of the wing, as outlined, means that trailing edge flap controls can be laid out to maintain their effectiveness at very high angles of attack. Since a certain portion of

this flap must be used to provide high lift and roll control, the amount available for longitudinal trim is limited, so that for the XB-35, for example, the total available nose-up pitching moment coefficient is .15 as compared to .30 for a conventional aeroplane. This limited control plus the fact that the main wing flaps apparently cannot be made self-trimming and impose a diving moment in the landing condition reduces the available C.G. range in per cent. of the m.a.c. as compared with conventional aeroplanes. The XB-35 has a C.G. range of only 5 per cent. or 6 per cent. as compared with conventional values in the order of 10 per cent. or 12 per cent. This comparison is somewhat misleading, however, because the all-wing aeroplane may have a greater comparative m.a.c. in view of its somewhat lighter wing loading. It is also much easier to arrange weight empty and useful load items span-wise within close m.a.c. limits than in conventional types.

Where manual control of the elevator is employed the stick-free stability and control of all-wing aircraft are impaired by separation of the flow from the upper surface of the wing near the trailing edge, causing up-floating tendencies at higher lift coefficients. If not corrected these up-floating tendencies lead to stick-free instability and, in some cases, to serious control-force reversal at high lift coefficient. Aerodynamic design refinements devised and tested by us to date have not provided a satisfactory solution to the up-floating tendency. For small aeroplanes these undesirable forces can sometimes be tolerated, but for large aircraft the only solution found so far has been the employment of irreversible full power-driven control surfaces.

LATERAL STABILITY DERIVATIVES.

It is when considering the lateral stability and control factors that the difference between the all-wing and conventional aeroplanes becomes most apparent. Fig 20 compares the XB-35 factors with those of a conventional aeroplane. It is reassuring to state that despite the large differences apparent, the dynamic lateral behaviour of the XB-35 type is quite satisfactory, as will be discussed later.

Derivative (per radian)		XB-35 $C_L=0.3$	XB-35 $C_L=0.6$	Conventional C_L~Cruise
$C_{n\beta}$	Weathercock Stability	0.020	0.026	0.060
$C_{l\beta}$	Effective Dihedral	− 0.029	− 0.057	− 0.070
$C_{y\beta}$	Sideforce	− 0.050	− 0.075	− 0.600
C_{nr}	Damping in Yaw	− 0.007	− 0.010	− 0.080
C_{np}	Yaw Due to Rolling	− 0.011	− 0.022	− 0.050
C_{lr}	Roll Due to Yawing	0.06	0.12	0.15
C_{lp}	Damping in Roll	− 0.44	− 0.44	− 0.45

Fig. 20.
Comparison of lateral stability derivatives for XB-35 and conventional aircraft.

Definite requirements for the weathercock stability $C_{n\beta}$, depend to a large extent on the aeroplane's purpose, but positive weathercock stability is always required. The swept-back wing has inherent directional stability which increases with increasing lift coefficient; but this is not considered sufficient for satisfactory flight characteristics under all circumstances and must be supplemented by some additional device. The wing-tip fin has been favoured by some since it gives the largest yawing lever arm and provides a suitable rudder location. However, as previously pointed out, wing-tip fins may be unsatisfactory at the stall. For the XB-35 configuration, effective fin area is provided in large measure by the side force derivative of the pusher propellers.

RUDDER DEVELOPMENT.

Rudders for all-wing aircraft are perhaps the chief control difficulty. Unless large fins are used a conventional rudder cannot be employed. If large fins and rudders are used, an objectionable adverse side force due to rudder is inherent, since the rudder moment arm is small and the side force comparatively great.

The use of pure drag rudders is feasible on the all-wing type because it is not necessary from a performance standpoint to fly at zero yaw. Thus in the case of an engine failure equilibrium conditions involving a yaw angle and the resultant corrective yawing moment do not involve appreciable side forces and associated bank angles, nor noticeable drag increases. Thus the rudder is used only rarely for trim and its drag is therefore unimportant.

Of the many types of drag rudder investigated, a simple double-split trailing-edge flap at the wing tip has been found to have the most satisfactory all-round characteristics. This arrangement permits the simplest construction and allows combination of trim flap and rudder in the same portion of the trailing edge. One disadvantage of this type is its comparatively low effectiveness at low angles of rudder deflection, which may be remedied by the employment of a non-linear pedal-to-rudder linkage in the case of power-operated rudders.

EFFECTIVE DIHEDRAL.

Considering now the effective dihedral $C_{l\beta}$, it is apparent that sweepback is the essential difference between the all-wing and conventional aeroplanes—a difference that will disappear as flight speeds increase and it becomes necessary to employ the desirable high-speed characteristics of swept wings in conventional tailed configurations. For swept-back wings $C_{l\beta}$ increases quite rapidly with lift coefficient which gives difficulty only when its value becomes too large. It is unimportant for either flight ease or for dynamic stability and control characteristics when it is near zero. Flight ease may indicate that a slightly positive effective dihedral is desirable while dynamic considerations point toward a slightly negative dihedral. Our practice has been to retain positive effective dihedral over the complete flight range.

ROLL CONTROL.

The rolling control for all-wing aeroplanes is essentially normal. When elevons are used rather than separated aileron and elevator control, certain variations from conventional craft appear, in that, with the upward elevator deflection required for longitudinal trim, the adverse yaw ordinarily due to aileron deflection disappears. On the other hand, if large up-deflections are required for longitudinal trim, the up-going elevon used as aileron loses effectiveness rapidly, thus reducing the available roll control at high lift coefficients. This is particularly undesirable when considering the increased dihedral effects of swept wings at high lift coefficient.

SIDE FORCE EFFECTS.

All-wing aeroplanes, particularly those without fins, have a very low cross-wind derivative; thus a low side force results from side-slipping motion. Some cross-wind force is probably important for precision flight, such as tight formation flying, bombing runs, gun training manœuvres, or pursuit. This importance arises because with low side force it becomes difficult to judge when sideslip is taking place, as the angle of bank necessary to sustain a steady side-slipping motion is small. This lack of side force has been one of the first objections of pilots and others when viewing the XB-35. After flying in the N9M or XB-35 the objection is removed, except for some of the specific cases mentioned above. For the correction of the lack of sideslip sense, a sideslip meter may be provided for the pilot or automatic pilot, and for very long-range aircraft there is a valuable compensating advantage in being able to fly

under conditions of asymmetrical power without appreciable increase in drag.

DYNAMIC LONGITUDINAL STABILITY.

The free longitudinal motions of any aeroplane fall into two modes. The first of these is a short-period oscillation. It is highly damped for conventional aeroplanes and also for all-wing aeroplanes in spite of the relatively low pitch-damping, C_{m_q}. This somewhat surprising result is due to a coupled motion such that the vertical damping, Z_w, comes into play absorbing the energy from the oscillation. Also, low moment of inertia in pitch makes the small existing C_{m_q} more effective than a similar value would be in conventional types In tests on the N9M aeroplane this short-period oscillation was too rapidly damped to obtain a quantitative check. The combination of low static stability in pitch, as previously described, and low moment of inertia in pitch results in periods of oscillation for all-wing aeroplanes that are comparable to those of conventional types.

The second mode of longitudinal motion is a long-period oscillation commonly called the phugoid. This is a lightly damped motion even for conventional aeroplanes, and seems slightly less damped for all-wing aeroplanes, because of the fact that they have relatively low drag, and drag is the chief means of energy absorption in this mode. N9M tests indicate that calculation is slightly optimistic in this matter, but still this phugoid motion is sufficiently damped so as to give no serious difficulties. Being a slow motion, it is easily controlled.

To date the criteria for the description of aeroplane dynamic stabilities are vague. In the past it has been thought that consideration of damping rates and periods of oscillatory motion were adequate, but it has become evident that some further criteria are necessary. Consideration of the angular response of aeroplanes to various unit disturbances may supply this need.

DYNAMIC LONGITUDINAL RESPONSE

The criterion of response is probably the only category in which the flying wing is importantly different from the conventional aeroplane for longitudinal motion. The action of the two types in an abrupt vertical gust is especially interesting, two factors combining to reduce the accelerations experienced by all-wing aeroplanes. These factors are the relatively larger wing chord and shorter effective tail length of the all-wing type. The first characteristic increases the time for the transient lift to build up and is the more important in reducing accelerations. The second decreases the time interval between the disturbing impulse at the lift surface and the correcting impulse at the effective tail, so that the aeroplane tends to pitch into the gust. This latter characteristic is a matter of concern to pilots, since a disturbance in the air is likely to leave them farther from trim attitude, consequently requiring more active pilot control in rough air. It is believed, however, that automatic control will effectively eliminate this difficulty.

The response of the all-wing aeroplane to elevator deflection seems entirely adequate. It errs, if at all, on the side of over-sensitivity because of low C_{m_q} and low moment of inertia in pitch. Fig 21 illustrates this effect.

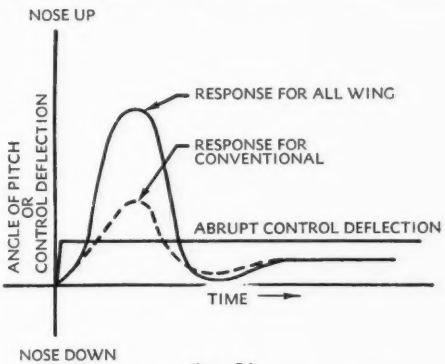


Fig. 21.
Response of all-wing and conventional aeroplanes to elevator control.

As is seen from the curves, an abrupt control movement giving the same final change in trim speed for a conventional and a comparable all-wing aeroplane results in a larger initial swing in pitch for the all-wing.

DYNAMIC LATERAL STABILITY.

As with longitudinal motion, there are two characteristic modes that are of interest laterally. The first of these is the spiral motion which is usually divergent on modern aeroplanes, thus uncontrolled flight results in a tightening spiral. This slight instability seems favoured by pilots. All-wing aeroplanes have readily acceptable characteristics in this mode requiring from 15 to 20 seconds to double amplitude. In general, any time greater than five seconds to double amplitude is considered acceptable.

The second mode, the "Dutch Roll" oscillation, is more critical for all-wing aeroplanes, particularly at low speed, high weight and high altitude. All-wing aeroplanes seem comparatively bad in this respect because of the combination of relatively large effective dihedral and low weathercock stability and, for the conditions noted above as critical, are likely to approach neutral damping in the Dutch Roll mode. However, analytical determinations of this motion, using calculated damping derivatives, indicated less satisfactory characteristics than were obtained in actual flight tests. Because of a relatively low weathercock stability, the Dutch Roll is of a rather long period, in the order of ten seconds for the XB-35. It is usually assumed that for periods of such length, it is not important to have a high rate of damping since control would seem easily "inside" the motion. However, there may be particular instances where this is not true. For instance, in an all-wing aeroplane in which the rudder is particularly weak, the time of response to rudder control may be of the same order as the period of Dutch Roll motion. This would make directional control extremely difficult in a condition, such as landing, where the roll controls are not usable for changing heading. It is notable that for the very low weathercock stability commonly encountered in all-wing aeroplanes, the conventional solution of increasing weathercock stability to offset increased dihedral does not hold. Increasing C_{n_r} leaves the damping essentially untouched, but reduces the period and increases the number of cycles required to damp.

Another factor contributing to the relative lack of damping of all-wing aeroplanes in Dutch Roll motion is the low value of the damping coefficient in yaw, C_{n_r}. This appears to be inherent in all-wing designs, particularly if the use of fins is abandoned. For special occasions, when particular aeroplane steadiness is required (such as a bombing run), it is probable that the equivalence of such damping in yaw may be supplied by an automatic pilot, or by temporarily increasing the drag at the wing tips. This latter effect can be accomplished on the XB-35 by simultaneously opening both rudders and gives deadbeat damping in yaw.

DYNAMIC LATERAL RESPONSE.

As in the longitudinal motions, the amplitudes of response of an aeroplane in lateral motion are probably as important as the damping rates in determining free-flight characteristics. All-wing aeroplanes seem slightly rougher in turbulent air than conventional aircraft of similar weight. This is due chiefly to the reduced wing loading, but high effective dihedral and low weathercock stability may have an added effect. This is a matter of interest in fixing upon analytical criteria for the description of free-flight qualities. As mentioned above, increasing the weathercock stability for all-wing aeroplanes has a slight effect on the damping rates; however, it affects the amplitudes of response to gusts materially.

Some data from the free-flight tunnel of the National Advisory Committee for Aeronautics indicate that increasing weathercock

stability, even for all-wing aeroplanes, materially helps the "flyability" of the aeroplane. Another bit of evidence that is of interest in this connection has to do with the magnitude of the side force derivative, $C_{y\beta}$. Increase of this parameter improves Dutch Roll damping very materially but has virtually no effect on amplitude of response to gusts, according to calculations. Free-flight wind tunnel data again give tentative support to the investigations of response as a criterion by showing little improvement of flight qualities of models with increase of $C_{y\beta}$.

Flight tests of the all-wing glider shown in Fig. 10, in which the vertical fin, located aft on the ship's centre line, was varied in size from approximately 2 to 7 per cent. of the wing area, left the pilot somewhat undecided as to fin requirements except that the larger fin seemed somewhat easier to fly. Presumably, this was, in the light of the foregoing discussion, primarily because of the increased $C_{n\beta}$ the coincidental increase in $C_{y\beta}$ not being effective.

AUTOMATIC PILOT CONTROL.

The application of automatic pilot control to an all-wing aeroplane has certain difficulties which are associated primarily with the low value of $C_{y\beta}$. In conventional applications the fact that the aeroplane is side slipping is detected by either a lateral acceleration or an angle of bank. In an all-wing aeroplane neither of these indications exists except in an almost undetectable amount. Accordingly, it is necessary, in order to fly the aeroplane at zero sideslip, and therefore in the direction of its centre line, to provide a yaw-vane signal to which the pilot or automatic pilot will respond. This introduces some difficulty in automatic pilot design because for small disturbances the sideslip angle with respect to the wind, and the yaw angle with respect to a set of fixed axes, are nearly equal and opposite for a flying wing. The customary automatic pilot control on azimuth angle therefore tends to oppose the necessary control on sideslip. To avoid this difficulty it is necessary only to reduce the rate of control on sideslip to approximately one-third that on azimuth. This modification to a conventional automatic pilot was flown on the N9M with complete success.

PROBLEMS OF CONFIGURATION—SWEPT *vs.* NON-SWEPT WINGS.

Let us now turn to a consideration of the practical limitations in arrangement of the tailless aeroplane. They may be summarised briefly as sweepforward, sweepback, and a non-swept wing configuration. The sweep-forward arrangement requires the use of a large fixed load forward of the leading edge at the centre section for proper balancing of the aeroplane. Therefore, a fuselage with some substantial part of the weight empty of the aeroplane disposed therein is required. The swept-forward wing itself is unstable directionally and requires some type of fin for weathercock stability. To this must be added more fin area to stabilise the fuselage. In addition, it may be noted that the moment arm of the fin about the C.G. of the aeroplane is necessarily comparatively small, still further increasing the size of the required fin. If we add to the aerofoil a protruding fuselage and an unusually large vertical tail surface, we have departed from our basic all-wing concept. We have incorporated virtually all the elements of drag found in the conventional aircraft and have not accomplished our intent of improving efficiency. For the above reasons, which could be argued pro and con for hours, our company has done no active design and development work on aeroplanes with swept-forward wings.

An all-wing configuration embodying a straight, or non-swept wing, has been proposed and flown successfully in model sizes. It offers the serious disadvantage that suitable distribution of weight empty and useful load items is difficult and, if proper

balance is to be accomplished, most of the structural weight and useful load must be included in the forward 30 per cent. or 40 per cent. of the wing, leaving a large volume of space within the wing unusable. Such a configuration results in an unnecessarily large aeroplane to accomplish a given job and for this reason has not been considered seriously.

The swept-back arrangement exemplified by the various aeroplanes previously illustrated and described seems to offer the best configuration for a materialisation of our all-wing ideal. It can be balanced satisfactorily within quite wide ranges of sweepback, utilising almost all available volume within the wing for storage of useful load items. It seems to fly satisfactorily in many different configurations and the arrangement is such that large payloads can be carried virtually over the C.G., with the weight empty items so distributed as to cause little variation in C.G. position between the fully loaded and empty conditions.

WEIGHT DISTRIBUTION.

As has been pointed out previously, the permissible range of C.G. location is not overly critical in this type of aeroplane. It is, nevertheless, of great advantage to be able to load the aeroplane almost at will, without concern as to how the useful load is disposed and the swept-back configuration lends itself most suitably to such loading.

In the case of the XB-35, the useful load, consisting largely of bombs and fuel, can be readily disposed in suitable position about the C.G. While some fuel is located well forward and other fuel well aft of the desired C.G. location, under normal operating conditions the proper balance is readily maintained. In case of failure of one or more engines, it is necessary to pump the fuel from unused tanks to those supplying the remaining engines, but a simple manifolding system provides this facility.

Based on a great many studies of various types and applications of the all-wing principle, some practical limitations may be approximately defined. Where very dense (high specific gravity) payloads are contemplated, such as warheads or similar munitions, quite small units are practical, as demonstrated by the all-wing buzz bombs to which reference has been made. Medium-sized units having a span of perhaps 100 ft. and a gross weight of 50,000 to 60,000 lb., appear entirely practical for medium bombers and freighters. Here again the density of the useful load, both in payload and fuel, is comparatively high.

Aeroplanes designed to carry people need the largest volume of all. Even individual reclining chair accommodations require a minimum space of perhaps 40 cubic ft. per passenger, which is a density of only about 5 lb. per cubic ft. This is one-half to one-quarter the density of typical air cargo, and only 4 per cent. or 5 per cent. of the density of a warhead.

IMMEDIATE APPLICATIONS—ALL-WING AIRCRAFT.

It may be concluded, then, that the all-wing design is immediately applicable and practical for a number of military and cargo-carrying versions, and that the passenger-carrying aircraft are likely to be of rather large size and, in the immediate future at least, will provide only comfortable seating instead of the more luxurious appurtenances associated with long-range ocean travel.

An aeroplane of the XB-35 configuration and size can carry 50 passengers in comfort in the existing aerofoil envelope with adequate headroom for all, and with vision forward through the leading edge, downward through windows in the floor, and upward if desired. Passenger vision in a flying wing may be more satisfactory than in conventional types if we get used to the idea of forward vision rather than that provided by side windows. The really interesting views are likely to be forward and downward rather than to the side. An aeroplane like the

XB-35 will have cargo space for 40,000 to 50,000 lb. of air freight at a density of 10 to 15 lb. per cubic ft., in addition to the necessary crew and space for 50 passengers.

FUTURE POSSIBILITIES.

Turning now to future possibilities, it seems that considerable further aerodynamic refinement can be made over that already accomplished in all-wing types. Particularly if turbo-jets are used as the motive power, the minimum parasite drag may be reduced to .008 or less. This value is obtained by subtracting the drag of propeller shaft housings, gun turrets and other military protuberances from the XB-35 configuration and assuming an improved degree of aerodynamic smoothness of the aerofoil section. Boundary layer removal and the use of somewhat thinner wing sections may further appreciably reduce this figure.

A maximum trimmed lift coefficient of 1.9 for the all-wing configuration seems attainable by methods already suggested and possibly may be further increased by judicious use of boundary layer control in combination with turbo-jet power plants. It is our opinion that the ratio of $C_{l\,max}$ to $C_{D\,min}$ may be increased to a value of 235 within the not-too-distant future from our present actual achievement of about 130. In contrast, the years of intensive development of the conventional types already passed promise an improvement of less magnitude within a comparable time. In our judgment a trimmed maximum lift of 2.8 *vs.* a minimum drag of .020 seems reasonable to expect for large, long-range transport and bombardment aircraft of conventional type.

These estimates are, of course, completely arbitrary and controversial. However, if one cares to assume their validity, the following conclusions may be reached, based on methods and calculations used in the early part of this paper. The total minimum profile drag of the all-wing aeroplane in terms of the conventional will be from 40 per cent. to 59 per cent. The power required by the all-wing to maintain the same cruising speed as the conventional will be from 70 per cent. to 80 per cent. and, conversely, the maximum range of the all-wing, at the cruising speed of the conventional aeroplane, will be 143 per cent. to 125 per cent. The maximum range of the all-wing aeroplane at *its* best cruising speed will be 158 per cent. to 130 per cent. of the conventional, and the most economic speed will be from 125 per cent to 115 per cent. faster.

Under high speed conditions corresponding to full power of reciprocating, turbo-prop or turbo-jet engines, where the induced drag is assumed to be 20 per cent. and the parasite drag 80 per cent. of the total, the power

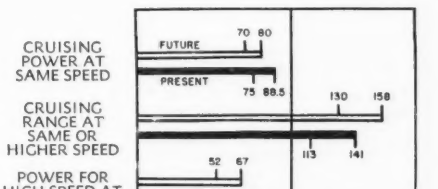


Fig. 22.
Graph of performance characteristics of all-wing aeroplane.

required to drive the all-wing aeroplane at the speed of the conventional aeroplane will be 52 per cent. to 67 per cent. and, conversely, the range will be 192 per cent. to 149 per cent. of the conventional aeroplane. The maximum speed of the all-wing aeroplane at comparable powers will be 124 per cent. to 114 per cent. of its conventional counterpart. These values are superimposed on those of Fig. 4, in Fig. 22, to give an idea of what possibilities for improvement appear reasonable in the next few years.

Different assumptions of comparative maximum lift and minimum drag values can be made to suit individual opinion, but it is believed that any reasonable assumptions will always result in an advantage to the all-wing configuration of such magnitude as to fully warrant whatever trials and tribulations may be associated with its development.

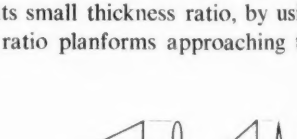
POSSIBLE SUPERSONIC APPLICATIONS

So far in this discussion we have purposely avoided transonic and supersonic considerations. This neglect is possibly a reasonable one when discussing commercial ventures, in view of the cost of higher and higher speeds. A reasonable degree of sweepback, such as is required in the type of aircraft under consideration, will permit speeds up to about 500 m.p.h. without involving great compressibility drag increases. For military aircraft, however, we cannot ignore the sonic "barrier" and its implications, and it is a reasonable assumption that sooner or later improved fuels will permit higher and higher operational speeds, even in commercial aircraft.

Based on present knowledge of supersonic flight, it will always be more difficult to carry a given payload for a given range at supersonic speed because of the additional wave drag encountered at these speeds. At transonic or comparatively low supersonic speeds, a plain swept-back wing appears to be one of the best possible configurations, provided that sufficient volume is available within the wing. Since the flow normal to the leading edge is subsonic over almost the entire wing surface, subsonic aerofoils with reasonably good subsonic flight characteristics can be used at these speeds. The all-wing design eliminates wing-fuselage interference as well as adverse interference between the tail surfaces and wing or body.

At higher supersonic speeds the problem of providing adequate volume is more difficult because of the fact that more and more fuel is required for a given range and that the percentage of thickness of aerofoils suitable for such use is much less than that satisfactory for subsonic flight. Save for one compensating factor, this problem of volume and size might well rule out the all-wing aeroplane for supersonic use, and certainly does limit its usefulness for low altitude flight. However, an attractive field of operation exists at very high altitude where air densities are low and therefore wing areas must be comparably great if suitable lift coefficients are to be maintained. If we design a frankly supersonic aeroplane to fly at, say, a Mach number of 1.6, with supersonic diamond-section aerofoils, the maximum cruising lift coefficient will probably be no greater than .15, and the corresponding loading must be held to 40 lb. per sq. ft.

The above figures are based on assumed operation at 60,000 ft. and an air density ratio of .094. Such an aeroplane might likewise be suitable for landing and take-off at low altitude, in view of its comparatively light wing loading, which would eliminate the necessity of high-lift devices. The practicability of the design depends on the relative density of the air at the altitude selected for cruising operation. If a sufficiently high altitude is chosen it seems quite possible that adequate volume can be secured in the wing, in spite of its small thickness ratio, by using low aspect ratio planforms approaching the triangular.



Type	Conventional	Delta
THICKNESS AT ROOT	1	1
TAPER RATIO	2:1	∞
THICKNESS RATIO	15%	7½%
ASPECT RATIO	8	4.5
ROOT CHORD RATIO	1	2
SPAN RATIO	1	.75
VOLUME RATIO	1	.833

Fig. 23.
Comparison of subsonic and supersonic all-wing aeroplanes.

Figure 23 shows comparative data on two wings having the same physical depth at the root, and identical wing areas. The conventional wing is of a type already proved practical for all-wing aeroplanes. The delta wing has thickness ratios suitable for supersonic flight, identical thickness and only slightly reduced volume. It should be quite suitable for all-wing aircraft of reasonable size. From the aerodynamic point of view it appears that with the delta wing it is possible to eliminate a substantial portion of the wave resistance and thus realise fairly favourable lift-drag ratios at supersonic speeds.

It is gratifying to those of us who have been working on all-wing projects for years to recognise the increased interest in the type evidenced in Germany toward the end of the war, and more particularly in England and Canada in recent years. For many years we received scant encouragement and often seriously questioned our own judgment, as well as our ability to achieve a successful solution to the many problems involved in the development of this type. The goals and rewards have always seemed well worth attainment, however, and I believe accomplishments to date have justified the effort required.

I hope this discussion may provide encouragement and incentive to those in Great Britain who have pioneered all-wing aeroplanes and that these projects, both here and in the United States, may profit by each other's mistakes and successes, thus bringing the two countries to the forefront in this important phase in the development of air transport.

The President, Sir Frederick Handley Page: After the Wilbur Wright Lecture they did not have a discussion, although Mr. Northrop had given them all a great deal about which to think. He would ask Dr. Roxbee Cox to propose, and Mr. Rowe to second, a vote of thanks. He had great pleasure in calling upon Dr. Roxbee Cox to do this, as he had been Vice-President during the past year in charge of the technical activities of the Society, and at the Council Meeting that day he had been elected President for the ensuing year.

Dr. Roxbee Cox (President-elect of the Society, Fellow): There was nothing more inspiring than a record of high endeavour; nothing more impressive than the logical development of a great thought from a picture in the mind to an achievement in the solid. That was what they had heard in the 35th of the Wilbur Wright Memorial Lectures, and that was why this lecture must rank with the finest in that remarkable series.

Mr. Northrop was not the first to have the vision of the all-wing aeroplane, Mr. Stephenson was not the first to have the vision of the steam locomotive. But they both had a gift more precious than priority in vision, the gift of being the right men at the right time to turn the vision into successful reality.

Mr. Northrop's timing was, in fact, almost uncanny. Not only did he produce swept-back wings at a time when scientists agreed that swept-back wings were the things to produce; he also brought his child to maturity at a time when the only power plant which could give it aesthetic perfection—and indeed minimum drag—reached maturity as well. All that remained now was to get rid of the wheels.

There were some who believed that an aeroplane should have the maximum of body with the minimum of wing—a mere projectile. There were others who believed it should have the maximum of wing with the minimum of body. To concentrate on the body was gross. But to aim for wings was to be on the side of the angels.

He proposed that they accord to Mr. Northrop a most sincere and hearty vote of thanks, with admiration in their hearts for his great ideas and magnificent accomplishments.

Mr. N. E. Rowe (Vice-President of the Society, Fellow) seconded the vote of thanks. He had had the pleasure of meeting Mr. Northrop in America on two occasions. On both those occasions he had been particularly impressed both by the energy and knowledge of Mr. Northrop and by his personality. He was never too busy to talk to anybody who was interested in all-wing aircraft. He was a man of great personal kindness and modesty and was always most generous with information which would be of any assistance to others.

He had given them that night a magnificent statement of the aeronautical difficulties which had been encountered and how they had been overcome. No doubt at some later stage he would describe

the great engineering difficulties which had been encountered and overcome. Mr. Northrop had the vision of a true pioneer, but he had both feet on the ground.

He had much pleasure in seconding this vote of thanks to his friend Jack Northrop.

The vote of thanks was carried with acclamation.

Following the lecture the Annual Council Dinner was held at which the following were present:—

Professor L. Aitchison, D.Met., B.Sc., F.R.I.C., M.I.Mech.E., F.R.Ae.S., Member of Council; Mr. E. J. N. Archbold, B.Sc., Grad.R.Ae.S., Member of Council.

Major General Clayton L. Bissell, G.S.C., Military and Air Attaché, U.S. Embassy; Lord Brabazon of Tara, M.C., F.R.Ae.S., Past President of the Society; Mr. Griffith Brewer, Hon.F.R.Ae.S., Past President of the Society; Sir John S. Buchanan, C.B.E., A.M.I.Mech.E., F.R.Ae.S., Member of Council; Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S., Member of Council.

Mr. S. Camm, C.B.E., F.R.Ae.S., Member of Council; Air Marshal The Hon. Sir Ralph Cochrane, K.B.E., C.B., Officer Commanding, Transport Command; Air Marshal Sir Alec W. Coryton, K.B.E., C.B., M.V.O., D.F.C., Controller of Supplies (Air), Ministry of Supply; Dr. H. Roxbee Cox., Ph.D., D.I.C., B.Sc., F.R.Ae.S., President-elect.

Commander W. L. Dawson, Liaison Officer, U.S. Naval Attaché's Office, London; Air Marshal Sir William Dickson, K.B.E., C.B., D.S.O., A.F.C., Vice-Chief of the Air Staff; Dr. G. P. Douglas, O.B.E., M.C., D.Sc., F.R.Ae.S., Member of Council.

Mr. A. G. Elliott, C.B.E., M.I.Mech.E., M.S.A.E., F.R.Ae.S., Member of Council.

Sir Richard Fairey, M.B.E., F.R.Ae.S., Past President; Mr. W. S. Farren, C.B., M.B.E., M.A., M.I.Mech.E., F.R.S., F.R.Ae.S., Member of Council; Sir A. H. Roy Fedden, M.B.E., D.Sc., M.I.Mech.E., M.S.A.E., F.R.Ae.S., Past President.

Mr. H. J. Goett, National Advisory Committee for Aeronautics.

Professor A. A. Hall, M.A., F.R.Ae.S., Member of Council; Mr. S. Scott Hall, A.C.G.I., M.Sc., D.I.C., F.R.Ae.S., Member of Council; Sir Harold Howitt, G.B.E., D.S.O., M.C., Deputy Chairman, British Overseas Airways Corporation.

Mr. E. T. Jones, O.B.E., M.Eng., F.R.Ae.S., Member of Council.

Sir Ben Lockspeiser, M.A., F.C.S., F.R.Ae.S., Member of Council.

The Rt. Hon. Lord Nathan, P.C., T.D., J.P., Minister of Civil Aviation; Mr. John K. Northrop, President, Northrop Aviation Inc.

Rear Admiral G. N. Oliver, C.B., D.S.O., Assistant Chief of Naval Staff (Air).

Sir Frederick Handley Page, C.B.E., F.R.Ae.S., President of the Royal Aeronautical Society; Capt. John B. Pearson, Jnr., U.S.N., Naval Attaché for Air, U.S. Embassy; Mr. W. G. A. Perring, F.R.Ae.S., Member of Council; Captain J. Laurence Pritchard, F.I.Ae.S., Hon.F.R.Ae.S., Secretary of the Society.

Air Marshal Sir James Robb, K.B.E., C.B., D.S.O., D.F.C., A.F.C., Officer Commanding, Fighter Command, R.A.F.; Mr. N. E. Rowe, C.B.E., B.Sc., D.I.C., F.R.Ae.S., Vice-President of the Society; Sir Archibald Rowlands, K.C.B., M.B.E., Permanent Secretary, Ministry of Supply.

Mr. Livingston Satterthwaite, Civil Air Attaché, U.S. Embassy; Air Marshal Sir Hugh Saunders, K.C.B., C.B., M.C., D.F.C., M.M., Officer Commanding, Bomber Command; Lord Sempill, A.F.C., F.R.Ae.S., Past President; Sir Oliver Simmonds, M.A., F.R.Ae.S., Vice-President; Rear Admiral M. S. Slattery, C.B., F.R.Ae.S., Chief Naval Representative, Ministry of Supply; Mr. W. R. Verdon Smith, President, Society of British Aircraft Constructors; Air Marshal Sir Ralph Sorley, K.C.B., O.B.E., D.S.C., D.F.C., Officer Commanding, Technical Training Command, R.A.F.; Mr. H. A. Soule, National Advisory Committee for Aeronautics; Professor R. V. Southwell, M.A., F.R.S., F.R.Ae.S., Rector, Imperial College of Science.

Captain C. F. Uwins, A.F.C., O.B.E., F.R.Ae.S., Honorary Treasurer of the Society.

Dr. H. C. Watts, M.B.E., D.Sc., M.Inst.C.E., F.R.Ae.S., Member of Council; Mr. H. E. Wimperis, C.B., C.B.E., M.A., F.R.Ae.S., Past President; Mr. L. A. Wingfield, M.C., D.F.C., A.R.Ae.S., Solicitor to the Society.

THE ROYAL AERONAUTICAL SOCIETY

The 710th Lecture read before the Society—on 10th April 1947 at the Institution of Civil Engineers, Great George Street, London, S.W.1. In the Chair, the President, Sir Frederick Handley Page, C.B.E., F.R.Ae.S.

A REVIEW OF PRODUCTION PROBLEMS IN RELATION TO AIRCRAFT DESIGN

by

Mr. C. E. FIELDING, O.B.E., A.F.R.Ae.S., M.I.P.E.

Mr. Fielding was educated at Oldham Technical School and Manchester College of Technology. He was apprenticed with T. & R. Lees, Hollinwood and joined A. V. Roe & Co. Ltd. in 1917 *in the Materials Test House and Jig and Tool Design. In* 1920 *he was appointed Works Manager and in* 1921 *Chief Inspector. In* 1927 *he became Assistant Works Manager, visiting U.S.A. as a technical adviser to firms making Avro aircraft. In* 1937 *he became Assistant General Manager and in* 1942 *he was appointed Director in charge of Production.*

INTRODUCTION.

MY SUBJECT is too big to cover adequately in the time at my disposal and as I have been asked to emphasise the wartime experience in aircraft factories, I propose to confine myself to a few of the most interesting problems.

Because of the urgent necessity to produce aircraft quickly in wartime the production engineer has a greater influence on design than normally, and many design problems are usually settled by a compromise between the requirement of the designer and the production engineer.

The designer attempts to satisfy the aerodynamic requirements at the lowest possible weight and the production engineer has to consider the shop equipment and floor space available, the type and availability of labour and ensure that the aircraft can be built in a minimum of man-hours.

To accomplish this it is essential to keep details as simple as possible, keep the number of details down to a minimum and create unit assemblies to a maximum. I will try and illustrate some of the ways this can be, and was, achieved.

Assembly operations of one form or another account for up to 80 per cent. of the man-hours required to build an aircraft and are therefore the most fruitful source in the saving of man-hours.

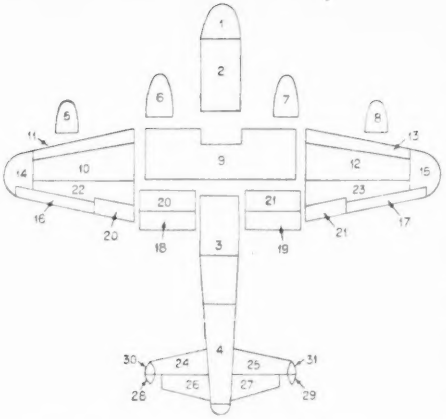
I do not suggest that details do not matter, but when considering detail design the assembly problem must be kept in mind.

One of the early problems in the design of an aircraft is the dividing of the aircraft into its various components.

Figure 1 shows the breakdown of a large bomber aircraft with an all-up weight of approximately 70,000 lb. and divided into 31 major components.

This breakdown is done to enable the components to be manufactured in such a size that they can be transported by road or rail and enable the aircraft to be maintained and repaired with the minimum amount of delay. It also allows the components to be made in dispersal factories situated away from the airfield. Other breakdowns are introduced purely to assist production and a good example of this is shown in Fig. 2.

Figure 2 shows a front section of the fuselage which was broken down at this point to give more accessibility for the fitting of equipment. All the equipment is installed ready for butting up to the nose section, shown in Fig. 3. It can readily be visualised



1. Nose fuselage.
2. Front fuselage.
3. Rear centre fuselage.
4. Rear fuselage.
5. Port outboard nacelle.
6. Port inboard nacelle.
7. Star. inboard nacelle.
8. Star. outboard nacelle.
9. Centre section.
10. Port outer wing.
11. Port leading edge.
12. Star. outer wing.
13. Star. leading edge.
14. Port wing-tip.
15. Star. wing-tip.
16. Port aileron.
17. Star. aileron.
18. Port c.s. flap.
19. Star. c.s. flap
20 Port c.s. trail. edge.
21. Star. c.s. trail. edge.
22. Port o.w. trail. edge.
23. Star. o.w. trail. edge.
24. Port tailplane.
25. Star. tailplane.
26. Port elevator.
27. Star. elevator.
28. Port rudder.
29. Star. rudder.
30. Port fin.
31. Star. fin.

Fig. 1.
Component break-down.

how inaccessible it would be if the equipment had to be fitted with the nose portion attached.

The introduction of this joint certainly saved many assembly hours and floor space on account of the improved accessibility and made it possible for more men to work on each section at the same time.

To get the maximum benefit from such a breakdown it is essential that each component should be a complete unit, with all services fitted, electrical wiring terminating with plugs and sockets and flying controls, hydraulic pipes, and so on, at an easily accessible join. Each section can then be tested, passed by inspection and passed on to the aerodrome for final assembly.

With this type of unit construction it is essential for the design office, when starting the project, to make sure that all drawings are tabulated and arranged in such a way that each component is treated as a separate unit. They must make it possible to completely equip each section of the fuselage before joining the sections together.

Such an arrangement as mentioned enabled a large bomber aircraft to be delivered after only four days' work at the final assembly factory. This period of four days covered the complete erection of the aircraft, flight testing, fitting armaments, and so on, and wiring the aircraft out for final delivery.

This quick turn-round saved a lot of floor space and resulted in reaching a higher peak of production than was originally thought possible and, assisted in bringing down the man-hours.

It will be realised that in order to assemble aircraft with such rapidity and also to service

Fig. 2.
D.2, looking aft.

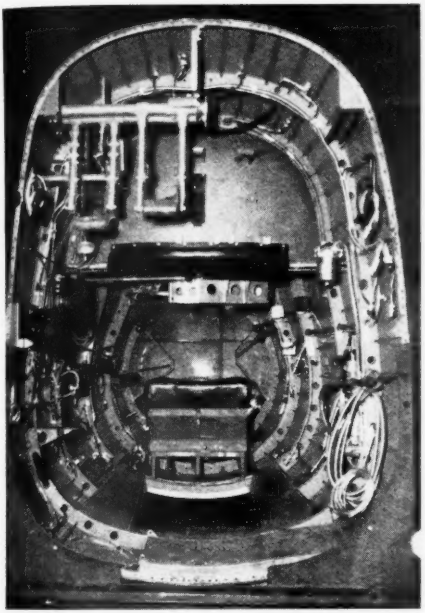


Fig. 3.
D.1, looking, forward.

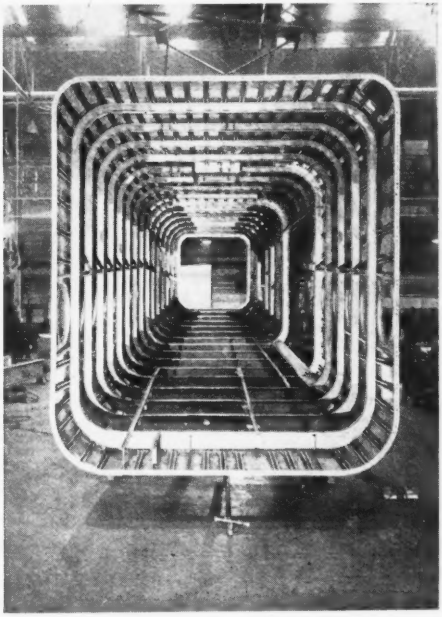


Fig. 4.
York D.3 shell.

the aircraft efficiently, it is absolutely essential that the interchangeability of components and sub-assemblies should be arranged at the earliest opportunity in the design stage. Close co-operation between the designer and the production engineer is necessary to make sure that all joints and attachments are designed so that they can be jigged satisfactorily.

The design and manufacturing of the interchangeability media required to control the manufacturing of assembly jigs should have top priority, otherwise delays and difficulties will arise.

The next major point to be settled between the production engineer and the design staff is the type of structure to be used.

There are two main types of structures used at the moment (1) riveting the skin to the stringers and formers, or (2) riveting of the skin to the stringers only. The skin/former/stringer combination does not lend itself easily to production and is more expensive in man-hours because all the operations have to be done in the main assembly jig, and the riveting is more extensive, whereas in the skin/stringer combination, a breakdown of skin panels and stringers can be arranged more easily. This is illustrated in Fig. 4 which shows a fuselage which is built up of eight sub-assembled panels, the four corner skin panels and the four side panels having been previously riveted together, by either re-action riveting, machine riveting or, if required, spot welding.

Figure 5 shows some of these panels in detail. It will be seen that, in addition to the stringers, all other auxiliary brackets, window frames and stringer attachment points are located during the sub-assembly stage, thus eliminating some of the locating points in the main assembly jig. This is an important point because the main assembly

jig is an expensive item and time saved means less jigs. In addition to saving man-hours, it also saves additional floor space. Another interesting development in this skin/stringer combination is shown in the next few figures. This is another effort which is being made to cut down the time in the main assembly jig to a minimum. Fig. 6 shows a complete floor of a fuselage in its assembly jig. During this operation floor panels and inspection holes are located and the inspection covers fitted.

Figure 7 shows the same floor with the frames bolted to it. The stringers can be bolted to the formers without any other assembly jig, because the formers are drilled for location of the stringers around its perimeter and the stringers are pre-drilled at the requisite pitch for the formers.

All this work can be done before the unit is placed in the final assembly jig as shown in Fig. 8. A further development is now under review to fasten the skins and the stringers together before the stringers are bolted to the formers and experiments are being made in the use of spot or seam welding in specially designed sub-assembly fixtures which will locate all stringers accurately. This, again, will cut down time in the main assembly jig.

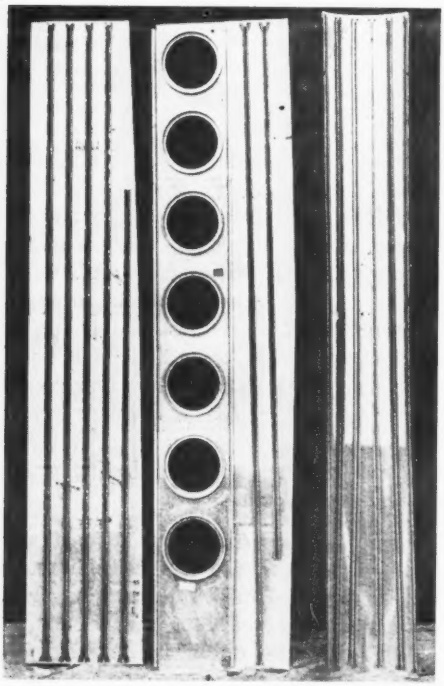


Fig. 5.
York skins..

Transport formers are the main reason why good type assembly jigs are required. It will be realised that this type of Butt joint as shown in Fig. 9 has its own peculiar problem. It is important for the joint surface to be true, otherwise stress will be induced in the structure when it is bolted together; also, deformation of the shape will take place. This is controlled by having robust end locations on the main assembly jig which have a true machined face. The former is bolted firmly to this face and is not released until the fuselage structure is completely riveted. This type of transport joint assembly has been used successfully on pressurised aircraft.

I would now like to say something about riveting methods. The designer would like to see all the aircraft structures riveted with flush type rivets, whereas the production engineer prefers the mushroom head type because it is easier from a production point of view. On medium-speed aircraft, the mushroom head rivet can usually be used without detriment to flying characteristics, whereas on a high speed type of aircraft, it is essential to use flush type riveting.

During the design stages of a recent pressurised commercial type of aircraft, a series of tests were carried out to investigate the pressure tightness of mushroom head riveting and flush type riveting. It was found that by slightly overdriving the rivets, the leakage rate at a stringer to skin riveting joint was negligible, and it was found that approximately 200 lb. of sealing compound was saved, because sealing compound was only used at skin lap joints.

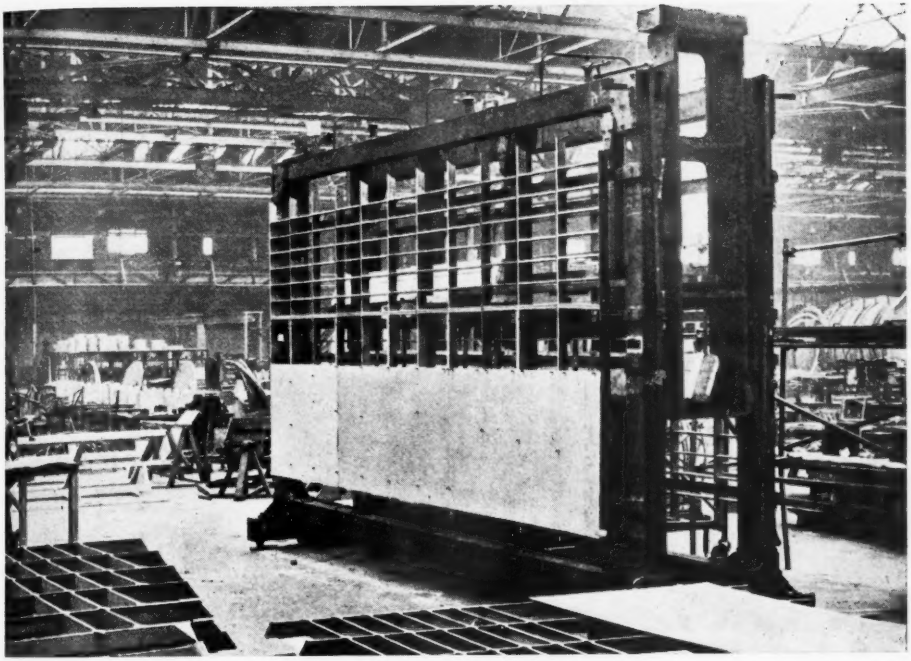


Fig. 6.
Tudor floor in jig.

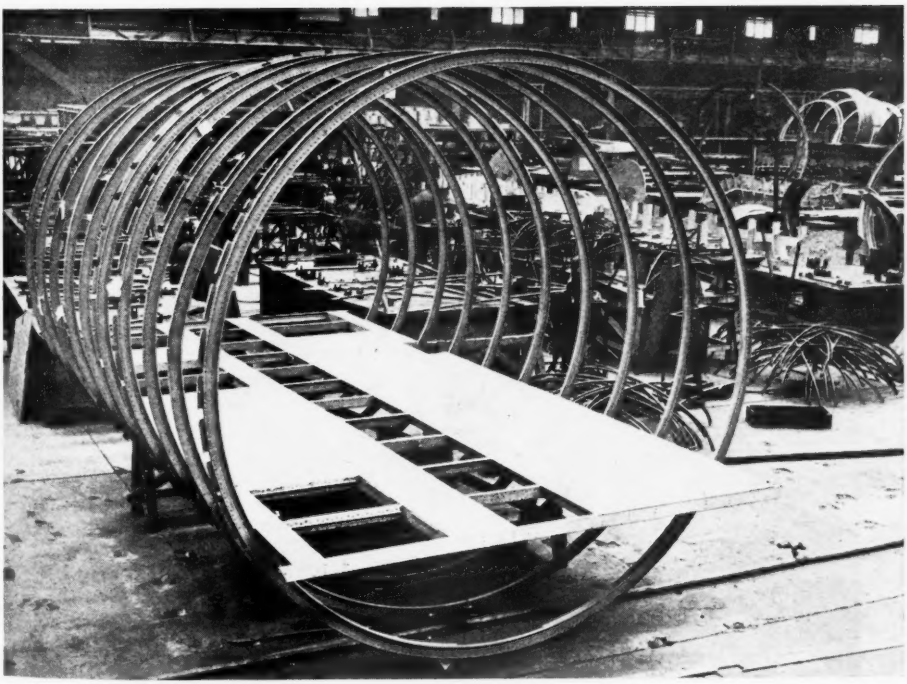


Fig. 7.
Tudor floor with formers out of jig.

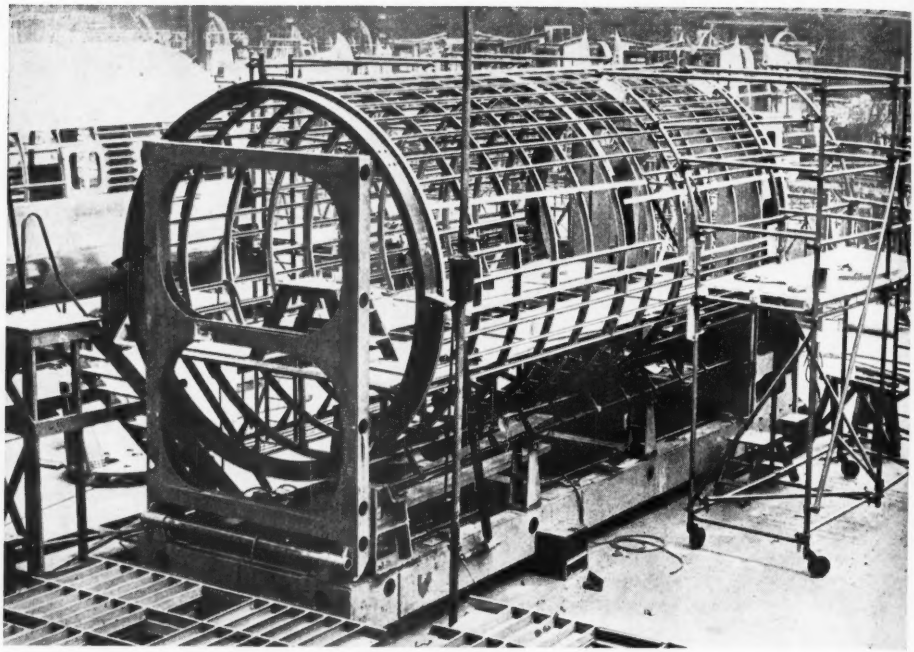


Fig. 8.
Tudor floor in fuselage assembly jig.

Fig. 9.
D.1 and D.2 Tudor.

The type of fuselage structure decided on automatically decides the type of fuselage former which will be used. Should the skin/stringer/former combination be used, the tooling of the formers becomes a major tooling operation because the outer edge of the former has got to be notched to suit the stringers.

In the case of skin/stringer combination, however, this is simplified and if a circular or oval shaped fuselage is required, formers can be rolled as a continuous member. With the square-sided fuselage, the fuselage formers become straight rolled sections for the side members with a standard pressing for the corners. The square-sided fuselage, as shown in Fig. 4, was arranged so that a standard radius was used at all four corners, which enabled a good quality mechanical press tool to be manufactured.

It will be seen from remarks on fuselage structures that, from a production point of view, the skin/stringer combination is the better of the two.

The manufacture of all-metal wings and tailplanes is a case where the designer likes to get his structure weight down to the minimum. Here again, many combinations of spars, ribs and stringers can be used.

On medium-speed aircraft, the two-spar wing seems to have advantages and is most common to-day. The spars can either be of the braced girder type or the solid web type. As stated earlier, the point to remember from a production point of view is to keep the number of detail parts down to a minimum. The girder type of spar to my mind requires too many details to produce, and I suggest that the solid web type of spar, with solid top and bottom booms is the cheaper (Fig. 10).

Should a detachable trailing edge or leading edge be required, the bolts that are used for fastening the spar booms to the webs can have a stud machined on their heads to take these components. On the outer wing spar where a taper boom is required, a standard rectangular extrusion is taken and slit along its length to give the correct angle, thus manufacturing two booms from one extrusion as shown in Fig. 11.

The method of attaching the booms to the web has been subject to quite a lot of development. Plain bolts in a .002 in. limit reamed hole have been used extensively, but when our peak production had to be raised we found that the drilling and reaming of the holes, many of which were 3 in. long, was

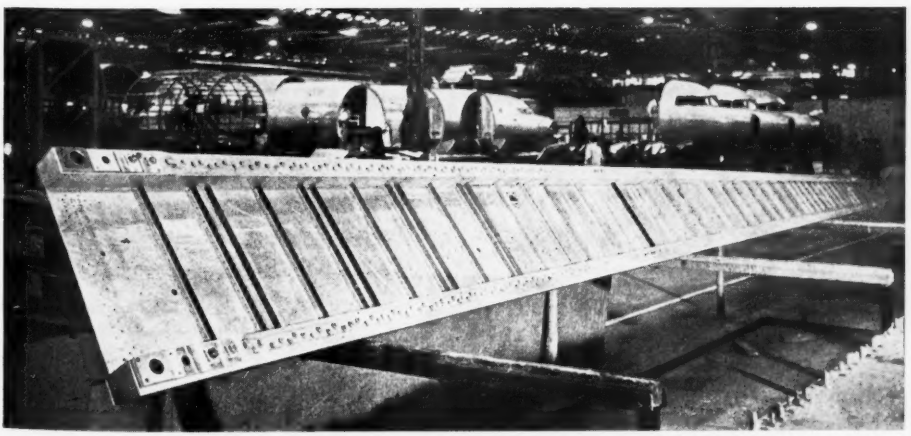


Fig. 10.
Assembled spar.

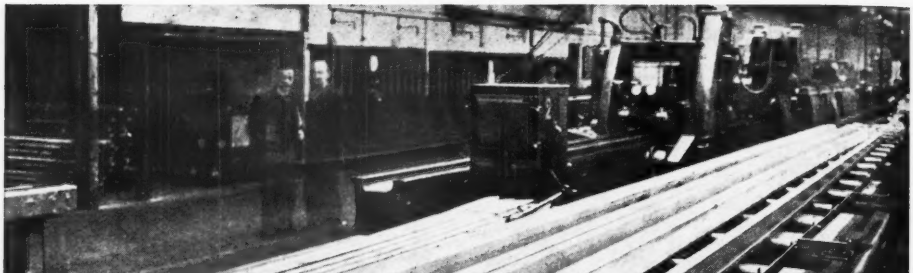


Fig. 11.
Spar booms.

our bottle-neck and a Parker Kalon bolt was developed specially for this job. The holes for these P.K. bolts were shorter, no reaming operation was required and this operation was reduced to less than half what it was previously.

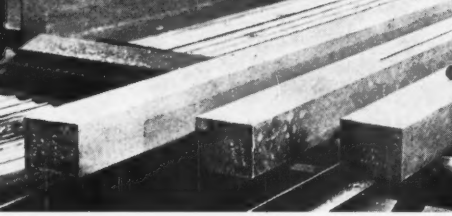


Fig. 12.
Spar bolt and P.K. bolt.

These Parker Kalon bolts, as shown in Fig. 12 with a standard bolt for comparison, are made of case-hardened steel and consist of a normal Parker Kalon bolt with a plain parallel portion under the head. This plain portion takes all the bearing and shear loads, the resulting attachment being as good in all respects as a normal bolted assembly. .

A special series of tests and extensive flying proved that the Parker Kalon bolts did not tend to work loose.

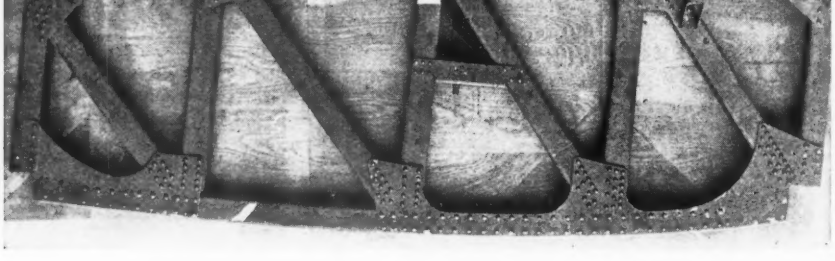


Fig. 13.
Girder rib.

When considering the manufacture of ribs for tailplane or mainplane, again the motto "Fewer details, more production" has been used, and the use of the girder type rib should, therefore be cut down to an absolute minimum.

In some cases for heavy load carrying, the girder type rib must be used, but this can be simplified if a standard rolled or extruded section is used for all members in the girder, as shown in Fig. 13.

It will be noticed that the members, all being of uniform dimensions, enable flat gusset plates to be used at the juncture of the booms and vertical or diagonal members.

The one piece rib meets the requirement of less details to the maximum, so we encourage its use.

Figure 14 shows a pressed rib as produced on the rubber press. The big advantage of the technique is the simplification of the tooling and, as tool manufacture is a controlling factor in getting aircraft into production, it has been our practice to use the rubber press technique.

The design office should, however, be ever alert to its use and avoid the flanges of lightening holes or swages being called for in the opposite direction of the outer flange.

Figure 15 shows this more clearly; the top illustration shows the incorrect method of swaging the lightening hole and below, the correct. The advantage of the latter case is that the rubber comes into contact with the web before it starts to do any work on either

Fig. 14.
Pressed rib.

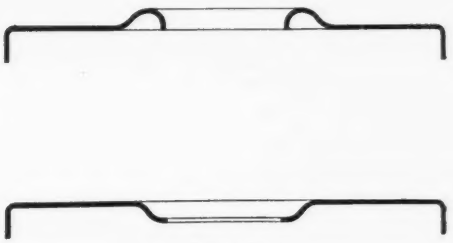


Fig. 15.
Rib diagram.

the edge or the lightening hole. It is also important that the lightening hole or any swages that are required in the rib flange are kept as far away as possible from any outside flanges, otherwise excessive square-up operations are required because the flanged edge of the rib is pulled, which causes distortion or buckling of the edge. This point is important because no matter how much squaring-up a flange is submitted to, it nearly always leaves irregularities, which all too often are shown up on the external skinning.

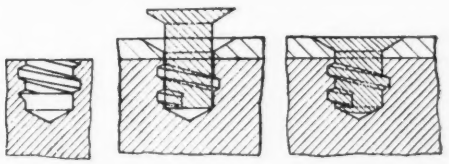


Fig. 16.
Plug rivet.

I do not propose to say much about the riveting of wing skinning, except to mention the case of plug riveting. This consists of drilling the hole through the skin and into a large mass boom too thick to be riveted in the normal manner. The hole is then tapped with an acme type thread, as shown in Fig. 16, and the rivet placed into the hole and driven home, thus causing the rivet to be forged into the thread of the screw. This method has proved very satisfactory. Parker Kalon screws have also been used but special care must be taken to ensure that the hole in the spar has been drilled square, otherwise

the head of the screw can be fractured easily.

Fuel tanks are housed in the main in the outer wing. At the beginning of the war our particular type of bomber aircraft was fitted with an integral fuel tank but as this could not be bullet-proofed, other tanks had to be designed.

A conventional riveted tank was first considered but this was thought to be too big a job and wasteful in man-hours.

Figure 17 shows the tank which was eventually developed. It will be seen that it is a welded tank with spot welded top hat stiffeners, the baffles being bolted to the stiffeners, the end pressings and longitudinal seams being gas welded. It is an extremely simple tank to make and is a good example of what can be achieved by co-operation between the design staff and the production engineer.

The capacity of one of the tanks was 585 gallons, and its weight, less bullet-proofing, was 186 lb., that is .310 lb. per gallon; with bullet-proofing the weight came out at .685 lb. per gallon.

The conventional riveted type of tank weighs on an average 1.29 lb. per gallon; thus as well as saving man-hours, weight was saved in this particular instance.

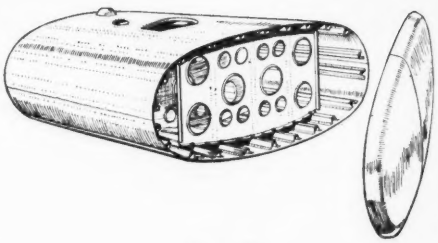


Fig. 17.
Tank diagram.

Flexible tanks are approximately 20 per cent. lighter than the welded tank, but when a flexible tank is used a structure has to be built to house the tank, so that the net saving in man-hours is reduced.

The arranging of fuselage equipment into sub-assemblies is an important requirement as space in the fuselage is restricted. Properly arranged sub-assemblies can save many man-hours on the equipment stages, resulting in more rapid movement of the fuselage through the shops.

Some good examples of fuselage sub-assemblies are shown in the next figures.

Electric wiring is one of the big jobs on the aircraft of to-day and the use of plugs and sockets saves many hours of laborious work of coupling up in usually inaccessible positions.

Figure 18 shows a number of electrical looms in a conduit which is assembled on the bench and bolted in the aircraft, so that the only connections to be made are in coupling up the plugs and sockets at the ends.

Figure 19 shows a typical instrument panel with electric wiring all complete with ends terminating in plugs and sockets.

As can be seen in Fig. 20, all the hydraulic equipment is mounted on to a panel, the items consisting of hydraulic reservoir, filter, relief valve, control valves, plus the emergency system and emergency hand pump. All the piping is completed as a bench assembly before putting into this fuselage.

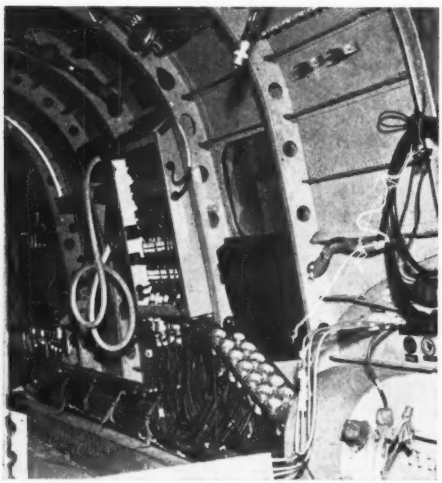


Fig. 18.
D.2. Looking forward.

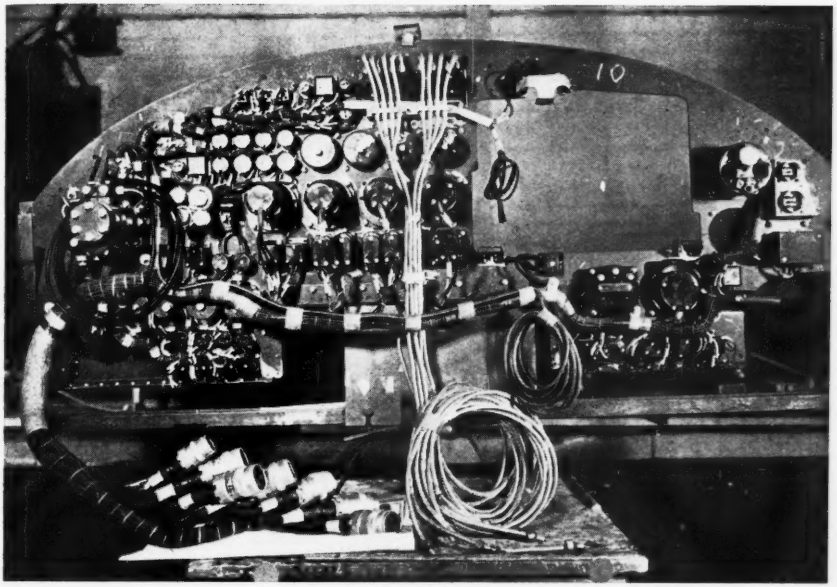


Fig. 19.
Pilot's panel.

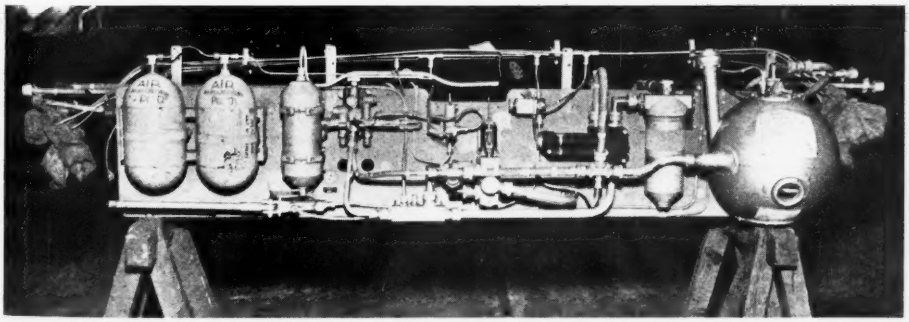


Fig. 20.
York hydraulic panel, front.

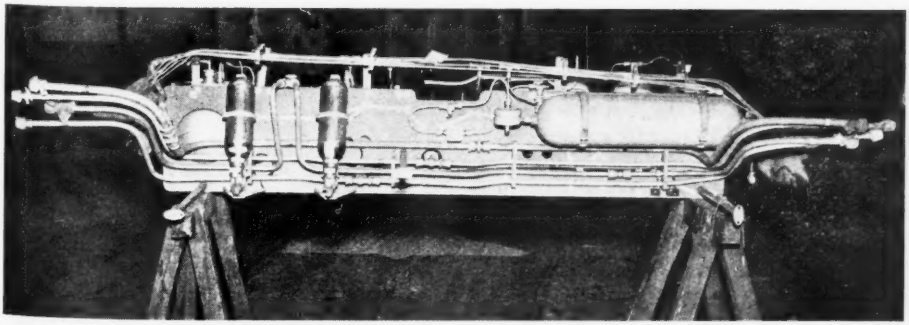


Fig. 21.
York hydraulic panel, rear.

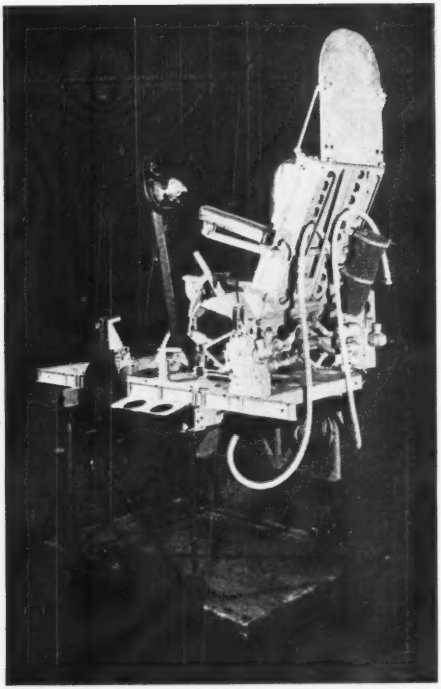


Fig. 22.
Pilot's seat.

Figure 21 shows a reverse view of the same panel. On the back of the panel is seen an air bottle for the air brake system, the air filter, control valve and fire extinguishers, together with pipe that passes from one wing to the other. This unit is fitted into the aircraft with twelve bolts.

Figure 22 shows a pilot's seat assembly mounted on its own particular portion of floor and carrying the control column with its brake system, the trimmer control box, complete hydraulic valves and other secondary controls.

Fig. 23 shows an air system mounted on a panel with its piping complete, thus saving an intricate job of fitting the pipe in an inaccessible corner of the aircraft.

The next three figures show methods of banking hydraulic pipes into units, clamping them together by the actual fairleads used on the aircraft and then mounting the complete bank of pipes and the fairlead by attachment bolts which hold the fairleads to the structure of the aircraft. This system of banking pipes not only ensures quick assembly, but guarantees interchangeability between such banks of pipes and/or separate detail pipes, as each pipe must be fitted to a jig which locates the ends of the pipes and also the attachment of the pipe and fairleads to the structure.

In order to assist with unit and sub-assembly, it is essential that the drawing office prepare the necessary G.A.'s showing these sub-assemblies on one drawing and arranging the bill of material in such a way that these can be readily extracted. The drawing office system, as arranged in my Company, enables this to be done easily because for any of the sub-assemblies shown in the illustrations, a separate drawing exists with a number and this drawing would carry its own bill of material. This has an

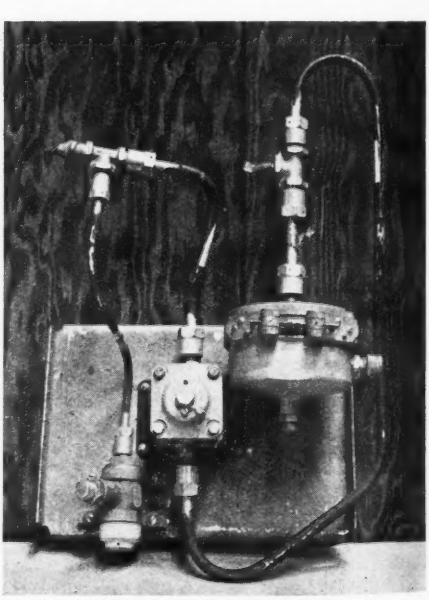


Fig. 23.
Brake pipe assembly.

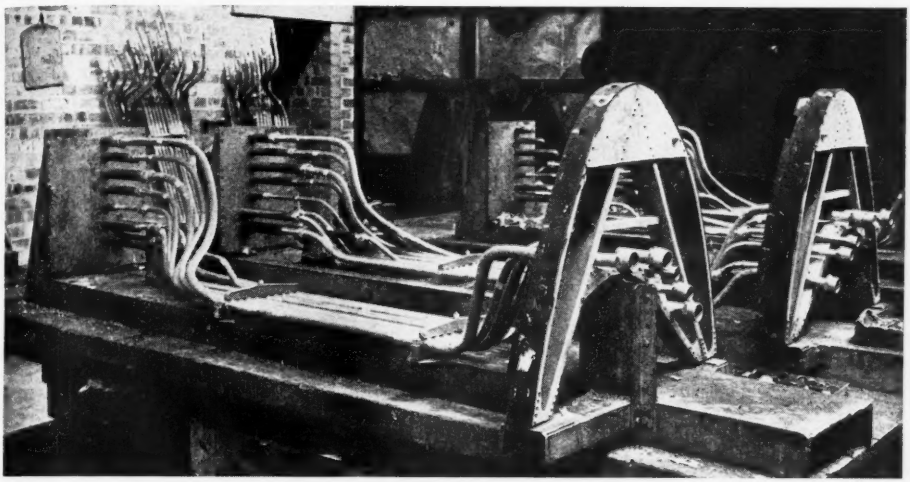


Fig. 24.
Leading edge pipe assembly.

additional advantage insofar as the standardisation of any of the assemblies is concerned.

Manufacturing of machine shop details can become a bottle-neck if they are not rigorously controlled. In order to overcome this problem it is advantageous to have a special production engineer who specialises in machine shop practice. This man should be detailed to check these problems during the project stages in the design office. The points which have to be watched are the use of standard tools and cutters wherever possible; to watch carefully to ensure that the equipment in the machine shop is capable of

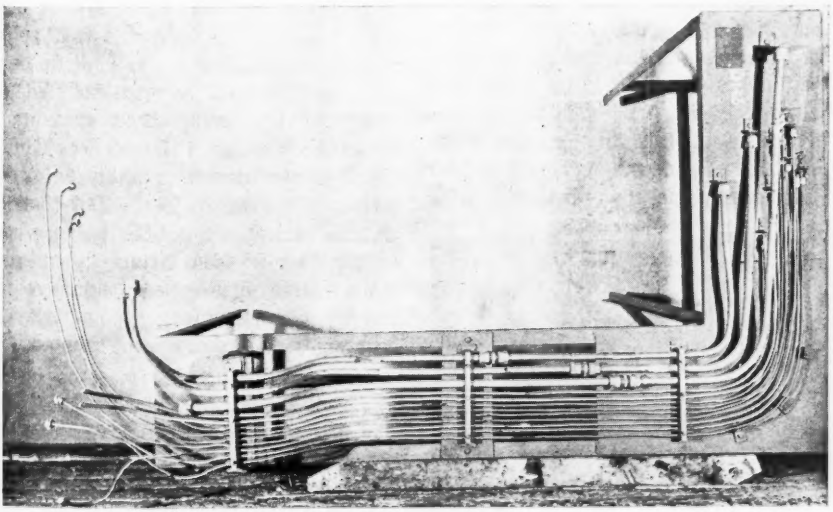


Fig. 25.
Pipe assembly in jig.

Fig. 26.
Stringer bracket.

dealing with the items designed; and to issue special instructions to the jig and tool drawing office to ensure that any special fixtures required are immediately covered.

While he is reviewing these points it is often found that a common stamping or casting can be used which, by a simple machining operation, converts the stamping or casting into various items.

Figure 26 shows such an example where a standard forging is taken and machined to make a number of items. In the foreground of the figure is seen the rough forging and placed around this are the separate items produced from this forging. This particular item is a stringer bracket and is varied by the machining of the attachment face to suit the shape of the fuselage.

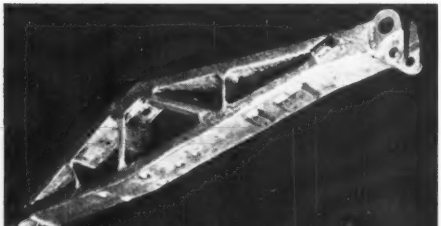


Fig. 27.
Undercarriage beam.

You can also find items which, by stamping or forging, can cut out detail parts but these have got to be carefully controlled, otherwise a bottle-neck can be created at either the forge or the die making companies.

Figure 27 shows a good example of the use of castings. This is an undercarriage support beam which carries the engine mounting sub-frame. Originally this was built up of steel plates and it can be visualised from this figure what a complicated structure this would become as a fabrication. Further developments have since taken place to give additional strength by forging this item. Such an arrangement as this, with its heavy cost of tooling and die manufacturing, can only be made if large quantity production is required, but from a wartime viewpoint it was an economical way of producing such an item.

Another aspect which must be borne in mind when reviewing machine shop items is that it is often possible to have an extrusion made which can be machined to a particular item. Fig. 28 shows such an arrangement, the item in question being a pi bracket to pick up the rib from the spar. The angle

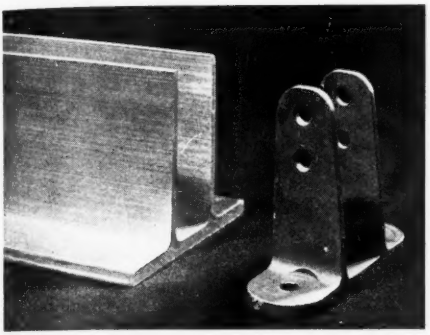


Fig. 28.
Pi bracket and extrusion.

of the leg varies but the distance between the two legs remains constant, so again it is possible to machine innumerable items from this standard extrusion.

A bottle-neck was created some time ago because of the manufacture of a collar bolt. Fig. 29 shows how this problem was overcome. The first drawing shows the bolt in question as a complete machined item. The second shows the bolt as a copper brazed collar attachment. This was investigated, but the equipment required for brazing, which would have meant a conveyor belt, could not be obtained in time so the third alternative, which shows a screwed-on collar, was used. This not only saved time in the machine shop but saved material.

In conclusion, I would say that aircraft problems exist to be solved by the complete co-operation of both the design staffs and the production engineers. If the production engineer would kill the bogey "It can't be done" and if the designers would keep before them the motto "Designed for simple people to build," the problem would be eased.

It is very hard to visualise an aircraft industry without problems, and as long as these problems exist for us to solve, we can say we are on the road that leads to finer and better aircraft.

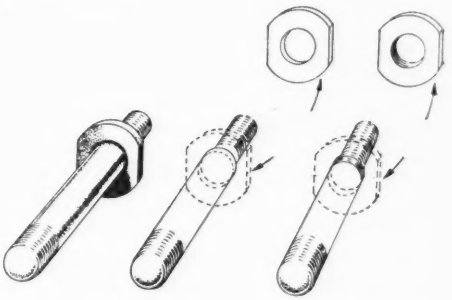


Fig. 29.
Spar bolts.

DISCUSSION

Sir John Buchanan (Short Brothers Ltd., Fellow): The Aircraft Industry was faced with a problem entirely different from that which had confronted it during the war. The breaking down of the Lancaster for war-time production had been illustrated but production in the aircraft factories now was relatively small and it was necessary to decide to what extent they were justified in breaking down the production of an aircraft into small components. How far did it pay to make extensive jigs, tools and fixtures for the production of a small number of aircraft? At what stage did the cost of tooling outweigh the saving in man-hours effected by that tooling in the manufacture of the aircraft?

A vexed problem which faced the design staff was that of riveting and welding; when to flush rivet, when to mushroom-head rivet and when to spot weld. At what stage was it profitable to use spot welding instead of riveting? Opinion was divided at his own works; some of the production engineers considered that it did not pay to spot weld at all and that riveting was cheaper.

He was a little disappointed that Mr. Fielding had not dealt with pipe bending by the more modern machines now in common

use for that purpose. There was some difference of opinion in the Industry as to whether pipe bending by machine was really economical. Was it economical in peace-time as it was in certain cases during the war?

The Industry had inherited from the war period a great bulk of expensive equipment in the form of rubber die presses, stretcher presses, drop stamps, and so on. At what stage did it pay to design for production on this equipment; for example, at what stage did it pay to design for manufacture on the fast-moving mechanical press with expensive dies instead of the slower-moving rubber die press with cheaper tools?

Mr. J. A. C. Manson (Director Aircraft Production, M.O.S., F.R.Ae.S.): The author had rightly used the title "A Review of Production Problems in Relation to Aircraft Design," and from that review they might draw conclusions and seek help in facing the future. For the future he suggested that the approach should be "design problems in relation to aircraft production," because if the designers were sufficiently acquainted with the production difficulties, many of the production engineers' problems could be designed out of the aeroplane right from the start.

He considered it axiomatic that the production engineer must impose no limitations on the development of aircraft design; rather must he use every ingenuity to achieve at reasonable cost what the designer required.

On the other hand, the good designer should always be associated with a good production engineer in order to get full value out of the products of his brains, and should —indeed, he must— have confidence in the ability and helpfulness of the production engineer. Then he would realise that the requirements of production were no shackles on his design, but gave an added zest and satisfaction in the achievement of a product which was slick and finished in conception and in detail.

The good designer and the good production engineer formed the most valuable team in the world of aeronautics, where Compromise was spelt with capital letters.

Mr. Fielding had said, rightly, that some 80 per cent. of the manufacturing man-hours on an aircraft were spent on assemblies and sub-assemblies; one of the most fruitful sources of time-saving in those stages was in having accurate details. The adoption of lofting full-scale layouts with photographic or lithographic reproduction, while not strictly part of the design process, was a method of conveying the necessary information to the shops, and was a most valuable ally of the production engineer in producing such accurate details.

Considering whether 80 per cent. of the man-hours *need* be spent on assemblies, he drew attention to some extracts from a paper read before the Institute of Aeronautical Sciences in the United States, published in the October 1946 issue of *Aircraft Production.* That paper had dealt with the production re-design of the Republic Sea Bee amphibian, and the results of that re-design were phenomenal. The structure weight was reduced from 1,260 lb. to 1,140 lb., the number of airframe parts from 1,800 to 450, the man-hours from 2,500 to 200, and the price, based on an output of 5,000 aircraft per year, was reduced from $1\frac{3}{4}$ million to 0.4 million dollars. Incidentally, the permissible all-up weight was increased from 2,900 lb. to 3,000 lb. and the number of passengers to be carried was increased from 3 to 4, thanks mainly, he supposed, to increased engine power and increased wing area.

Probably it would be said that that was an extreme case and that few aircraft could be designed for an output of 5,000 per year. But it certainly pointed the way for all designers, which Mr. Fielding had stressed twice in his paper. Simplicity, small numbers of details, easy assemblies; by those means the figure of 80 per cent. could possibly be

reduced, and with it the over-all number of man-hours.

Early in the paper the author seemed to imply that only in war-time had the production engineer a great influence in the design. There were two facets of the same problem in peace-time. One related mainly to civil aircraft, where the design and production technique to be employed must be related to sales, actual and expected, on which was taken the decision to put the aircraft into production; the other related to military where the purchasing authority, while placing orders for prototypes and certain specified production quantities for immediate peace-time needs, was in a position to specify that the design and tooling were to be based on greater quantities and rates of output which might be required in other circumstances.

But in either case the right solution could be reached only by the close team work of all concerned. He would like to see more thought and time put into the study of tender designs, particularly from the manufacturing point of view; the jigging and tooling should be considered in parallel with the aircraft design and should be related to the quantities and rates of output required. Undoubtedly that would mean a lot of work in the early stages, but he was convinced that it would amply repay the makers in getting started on the right foot once the actual project was put in hand. He would welcome the views of Mr. Fielding and others on that point.

The question of standardisation was not discussed by Mr. Fielding, but it was one of great importance from the production and maintenance points of view, and deserved more attention all round.

It was most important from the production and maintenance aspects that the maximum breakdown into components, assemblies and sub-assemblies, wiring looms and pipe assemblies, should be possible, consistent with no serious handicap on the designer. Mr. Fielding had shown some of the greatest examples of breakdowns which had been achieved in this country. Fuselage break joints cost weight, and in a civil aircraft, where every pound of payload lost on account of increased structure weight was worth untold revenue-earning capacity in the life of an aircraft, those considerations must be weighed against the costs involved in production, and more especially in maintenance, including lost revenue caused by aircraft unserviceability. It was a difficult problem for the designer, manufacturer and operator of aircraft.

In his opinion the moral to be drawn from the paper was that close team work was the right line to follow. The advent of very high speed aircraft would bring fresh problems of manufacture, such as the manipulation of thick gauge light alloy sheets, using a minimum of internal stiffeners to obtain superior finishes on aerofoil surfaces, the use of processes other than skin riveting; and in all those problems the designers and production engineers must face the future in close collaboration and with mutual respect for each other's problems and contributions to their final solution.

Mr. J. V. Connolly (College of Aeronautics, Associate Fellow): It was obvious that the primary method by which an aeroplane could be produced at the expenditure of a small number of man-hours was by keeping to a minimum the number of parts which the aeroplane contained. But apart from that generalisation they did not know how far that law applied, because if the aeroplane were larger than the Sea Bee mentioned by Mr. Manson, the parts must be composed of a multiplicity of details. A small aeroplane could be made with single sheets of material of a size up to, say, 6 ft. or so; but as the machines became bigger, the sheets would not become bigger automatically, and it became necessary to make a multiplicity of parts.

They did not want just general observations about the correct qualitative methods of solving a problem; they wanted something on paper. The analogy was that, if they

dealt with aerodynamics as they did with production problems, there would be a large number of people in the Industry and in the Ministries with certain ideas and certain experience, valuable experience but not necessarily objective knowledge and not necessarily always facts. If aerodynamics depended on a lot of design people having an idea in their minds of the general shape of a lift curve, a drag curve or a moment coefficient, with no real possibility of putting it down as an equation or as an actual curve with a specified limit of error, known experimentally, it would be extremely difficult to decide at any stage, or even to measure afterwards, what sort of job the aerodynamics people had achieved in relation to the physical possibilities in achieving any result.

In aircraft production they had not the equivalent of the Carnot cycle of efficiency. In the case of a steam engine or any other heat engine, the mechanical engineer could say that it was of a certain efficiency, say within 50 or 25 per cent. of the Carnot efficiency. But it would be a daring man who would say, from the production point of view, what was an absolutely efficient aeroplane.

Figures had been quoted by Mr. Manson, figures which were more or less generally known now as theoretical figures, showing a percentage variation of 1,000 per cent. between what one would expect to achieve by conventional methods and what was claimed to have been achieved by simplification. They knew roughly how that 1,000 per cent. difference was achieved; in respect of the number of airframe parts it must have been because of the 500 per cent. difference between the conventional and simplified airframes. But it seemed that they would not make any rapid progress until they could get down on paper some criteria of achievement, even though they be elementary. There were in existence a large number of statistics, of facts; Mr. Fielding had some of them and was interested in that aspect. But from those figures, unless they were related to a scale—in other words, unless they knew that certain things happened when they made 5,000 aeroplanes and other things when they made only two, and that between those points there were some consistent laws—the prediction and subsequent checking of any future examples obtained would be loose, qualitative and, he submitted, not at all scientific.

Every time an aircraft was designed, certain local problems arose. They would be solved by the skill and the team work of the design organisation and the production organisation; but those two organisations would tend to solve the problems against their own standards and, having reached a solution which satisfied their standards, it did not follow that it was the best possible objective solution.

He urged that they should do what had been done by those who had designed aeroplanes in, say, 1910, *i.e.*, that they should start putting down production results in a form in which they could be applied and checked, just as they had gradually acquired books on lift curves, drag curves and moment coefficients. He hoped that they could gradually build up a mass of data on production, and he, personally, was endeavouring to do that, but it depended most on the co-operation of other people in the Aircraft Industry who were interested, to put down certain facts.

He had found that a number of aspects had been studied from that point of view and that, instead of being random and uncoordinated, the most amazing correlations existed between measured facts. The percentages of deviation of some of the statistics from a theoretical curve or from an average curve were often less than the deviations which occurred in aerodynamics. The fact that this was so in a number of cases had convinced him that there was a possibility

of putting production work on to a scientific basis.

For example, T. P. Wright's 80 per cent. law for reduction in man-hours with increased quantities of aircraft produced, a law with which everybody in the production world was now fairly familiar, might have been an inspiration or it might have been based on quite a lot of work. It was postulated in 1936, and wherever results were available there was close agreement. He had results from Canada, Germany and this country, and a large number from America, and the agreement was closer than he would have expected in that class of work. After all, it was not possible to reduce it to simple components, to measure one or two definite quantities and isolate variables. He was sure that if they went right through the field of aircraft production and tried to correlate such factors as man-hours and numbers of parts in the aircraft, or man-hours and numbers of rivet holes, a great deal of concrete knowledge would arise which would help the design man, who wanted objective data, but who could not find time to study too many qualitative results in a field outside his own primary interests.

Mr. J. D. Stranks (Hawker Aircraft Co. Ltd., Associate Fellow): The problem of the relationship of production to design was of considerable magnitude. There could be no general relationship between these two main sections of an organisation which could apply at each and every constructing company. From experience they knew that a system which worked with success at one company, appeared to be totally different from one associated with another equally successful company. They could only assume that a system which had been built up by any successful company was, in fact, best suited to that company.

He considered that if the production people were let loose to any great extent at the design stage, the effect undoubtedly would be to cramp design, which, all would agree, was highly undesirable. A line of thought might be that to a great degree the production engineer must spring from the experimental departments, for those departments were facing the actual problems of the design people at the earliest stages. Frequently they were called upon to achieve results beyond the apparent capacity of their plant, and, as a result of their experiences, they were best able to advise on ways and means of getting down to the job in production.

An aspect which must be considered was how production problems could be most efficiently fed into the factory at the prototype acceptance stage. There were many in the pre-production departments who had been accustomed to coping with prototypes, well knowing that there was perhaps a 70-30 per cent. chance that the prototype design would go into production. He was afraid that the odds were turning in the reverse direction, and the question was how far could a firm afford to give attention to production problems when the aircraft were still at the prototype stage?

Could someone say at what stage it was economic to introduce forgings and castings, having regard to the total quantities on order? He would like some instruction as to whether they could look for economy becoming manifest at a quantity of, say, 50, or whether it was necessary to consider quantities of 500 before deciding that a casting or a forging was the economic solution.

Air Commodore D. F. Lucking (Fellow): Towards the latter part of the war he had been impressed by the great help it had been in repair and salvage operations to have the breakdown into components which was such a feature of the aircraft shown in Mr. Fielding's slides. The breaking down of the aircraft into easily-handled components not only helped production, but helped enormously in the operation of the aircraft, in that it facilitated rapid recovery and trans-

port from the scene of a forced landing or a crash, and subsequent repairs.

The paper, on a decidedly practical aspect of aeronautical engineering, was most welcome. He suggested that the Society might seek more papers dealing with production subjects, even broadly, as Mr. Fielding's paper had done, or perhaps with a narrower field such as, for instance, some particular type of riveting or machining operation.

He found it rather an interesting reflection, inspired by the remarks of Sir John Buchanan, whether they could afford to produce civil aircraft in small quantities. If they were to produce only in small quantities, and if the development costs were added to the production costs of a few aeroplanes only, the cost per item would be so high that civil aviation would find it harder than ever to pay for itself. The object of the Industry should be to produce aircraft likely to be required in large quantities. If only half a dozen of one type of aeroplane were produced, each of the half dozen would be very costly, because nowadays a very great amount of work had to go into the development of even a more or less conventional aircraft, let alone one of novel design.

Mr. F. H. Parker (Bristol Aeroplane Co. Ltd.): The discussion had not touched on the question of modifications, which aircraft manufacturers had to face. In his Company they had arrived at a figure, as a rough yardstick, of 15 per cent. of their total effort, as representing the amount of work going into modifications of unknown value. Did that agree with the experience of Mr. Fielding or anyone else, or had anyone found a way of evaluating the effort put into modifications, also bearing in mind that tooling was usually much upset by their introduction?

Miss A. Kennedy (Companion): Was the breakdown of operations in very great detail for production purposes, as practised during the war so as to employ semi-skilled labour, considered to be very uneconomic in normal times?

Mr. C. M. Barter (Ministry of Supply): The Service type and the civil type of aircraft should be completely differentiated in regard to production.

For the Service type it was up to the user to specify, right from the start, whether any particular aircraft was to be designed with a view to possible quantity production, or for purely development purposes in small numbers. The user should be prepared to meet the capital cost of laying out the design on a quantity production basis, even if only half a dozen were ordered eventually.

In the case of the civil type the circumstances were completely different. The firm concerned had to gamble on the quantity it would have to produce and would be able to sell; they had to decide in the first place whether large quantity production would be justified, as against the more expensive method of hand-producing a few.

The Service user of aircraft should also specify the breakdown aspect for maintenance purposes; that should not be allowed to become purely a production problem. The Ministry concerned should state that, from the point of view of maintenance, the aircraft must be broken down to parts of a certain size or of a certain character, and the weight price which had to be paid for that in loss of load, must be borne by the user Service, just as was the financial burden.

Mr. T. C. L. Westbrook (Assoc. Fellow): He agreed that the production engineer should be in right from the conception, but he believed that most prototypes had been made first, and only afterwards had steps been taken to make the aircraft easy for production; even the Lancaster had come out partly in that way.

There must be good inspection throughout in order to ensure good production and to avoid troubles in the drawing office and he urged that that inspection should include the

tools, for often the tools were so bad that the resulting jobs were inconsistent.

Apparently Mr. Fielding had taken it for granted that the locations must be on the various jobs; but it would be wise to show the locations on the drawings. There were many people who regarded any job they did as being good enough, and they would pass it through, so that that "good enough" attitude persisted throughout the construction of an aircraft; consequently, the aircraft was made more or less to drawings, but not quite to drawings, and the production was not good because consequently everybody bodged their jobs all along the line. If only the inspection of the details was right, they would do much better on the whole job.

Mr. R. S. Stafford (Handley Page Ltd., Fellow): In most firms it seemed to be the view that research and development were the prerogative of the design team. It seemed to him that if they were to achieve in production the advances in aircraft performance now shown to be theoretically possible, then the production departments must shoulder a considerable part of the burden of development. For instance, wings were now considered to limits of accuracy, with regard to waviness of the surface, of the order of 0.001 in. per inch of length. The making of those wings was a difficult production problem, and in the development work the production department should play an equal part with the design team.

Mr. Manson: Would Mr. Fielding give some idea of what he considered, from the production point of view, the ideal set-up as between the design, experimental and production engineering departments of a factory?

Sir Frederick Handley Page (The President, Fellow): He supposed the real basis for the production of aircraft was that first of all it was essential to know what they were going to make.

Changes were much greater and more frequent in the case of aircraft than in the case of motor cars, for example. Motor cars did not change at a very great rate in respect of their basic qualities.

In aircraft changes were rapid, and within reason, particularly in the case of Service aircraft, it was not so much the price as the performance which counted. If civil aircraft could be divorced from prestige flying, which was demanded from the national point of view; if civil aviation were concerned solely with commercial flying, then the change in technique would be much slower than at present, and the cost of the change in technique would be borne ultimately largely by the purchasers of tickets for travelling in the aircraft, rather than by the country as a whole.

The study of production as production was really a simple matter once the design was produced and they knew what had to be made. But at the back of it all there was the difficulty that they did not know what they had to make. That was illustrated by the changes that had been made from time to time in respect of wireless, and the way in which the fittings and wiring changed. Eventually a great many drawings might have to be altered because brackets had had to be put on the various ribs, the detail drawings and assembly drawings had to be altered, and there was a tremendous set-back, all caused by what was thought to be a simple alteration.

Could Mr. Fielding say anything about simplified design? He wondered whether he had considered what might be called simplified tooling equipment, a more simplified rubber press, for example, or other things by which they could produce interchangeable quality articles. It was obvious that they were not going to make thousands of machines of the Brabazon I size; therefore the technique in respect of that machine would be different from that applying to the Sea Bee. But even in the case of the Sea Bee it had not panned out exactly as planned; in spite of the figures which had been given

and the papers which had been read concerning their simplified production, the price had had to be advanced from time to time beyond that originally intended.

MR. FIELDING'S REPLY

Sir John Buchanan: An important factor in the breakdown of the fuselage was that of weight. His Company had got away with it in the case of the Lancaster; but in the next type they would not get away with it, because of the weight penalty.

With regard to the customer specifying the extent of the breakdown by reference to servicing problems, that was how the breakdown had started in the case of the Lancaster; the makers were told the maximum size of any component and that meant that they had to put in transport joints in order to bring all the components within the limits specified.

They had visions of spot welding fuselages, for it was thought that that would be a good thing from the pressurisation point of view. But from their experience of the riveted fuselage they were not worried about the pressure aspect and in his view, spot welding would be limited to small manageable components. On the big components there were many complications, one being the necessity to break the component down into a size which could be accommodated by the spot welder, and this usually meant additional joints and increased weight.

The question as to whether or not pipe bending should be done on machines depended on the quantities involved. For small quantities he did not think that elaborate jigs were required or necessary. By arranging standard bend radii wherever possible a Helgar type bender could be used to advantage, as existing adaptors could then be used. It was necessary to look after the interchangeability side of the job and this could be accommodated by the use of simple fixtures. The problem of skilled labour might be one of the deciding factors in considering how far to tool up that kind of job.

The hydraulic press was a most expensive machine to operate. His Company's practice was to run the press when the number of pressings required was sufficient to enable them to get value out of it, and they did not run it during the other part of the week.

Regarding the question of how far to tool up a job on small quantity orders, it was very difficult to lay down any hard and fast rule.

It was necessary to control interchangeability, accuracy of contours, and so on, and this required jigs and tools, but they should be kept as simple as possible. Regarding details, some of these came in the above category but on the remainder standard tools should be used where possible or semi free-hand methods adopted.

Mr. Manson: He agreed that production engineers had to take a lot of notice of the designer, particularly in regard to the new advanced types of aeroplanes; he was afraid that, with the high speed aircraft coming along, the production engineers would lose a lot of ground. He could only say that they would have to do the best they could; and he assured them that something would be done about it.

He strongly supported the idea of reducing the number of details, as on the Sea Bee, but could not visualise the possibility of producing a complete aircraft for 200 man-hours and recalled the President's comments that the price had been increased from time to time.

Mr. Connolly: During the war, when they had had long runs, it had been possible to get quite a lot of data on production man-hours, and in the case of the Lancaster he had found that it did run to a definite curve. It was an 86 per cent. curve, not the 80 per

cent. curve claimed by the Americans. But the American figure covered all the aircraft manufacturers, some of whom were quite new at the game; an established aircraft manufacturer should obviously start off better than one who had not been doing that job before, and therefore there was less room for improvement, so that the curve was flatter. His Company were trying to obtain data covering the quantities and the variety of types they were producing at the moment; but it was difficult, on account of the unstable conditions during their retraction period and he was afraid that it would be some considerable time before they could obtain reliable data.

Mr. Stranks: The practice of the experimental department advising on production problems was encouraged in his Company's factory, and they used in production a large number of the tools that were made by the experimental department. In order to look after that side of the business, one or two process engineers were devoting their time solely to maintaining liaison with the experimental department; they arranged which tools would be suitable for use on production, which required a little alteration, and so on.

The decision as to when it was economic to introduce forgings depended on how complicated was the item under consideration. It was necessary to compare how much it would cost to machine the item out of bar, and how much it would cost to produce and machine a forging.

Mr. Parker: With regard to modifications, he had not a figure such as that of 15 per cent. mentioned. Many times he had felt that an aeroplane was nearly all modifications.

Miss Kennedy: There was still semi-skilled labour in their factory and it was employed wherever it could be employed. It all depended on the job, and how far they could afford to tool it; it was necessary to tool a job for semi-skilled labour.

Any machine, to be easily maintained, must be easily assembled.

Mr. Westbrook: He agreed that inspection played an important part in making sure that the tools made a satisfactory job, that the items produced were in accordance with the drawing and that the part as drawn was correct for the requirements of the job.

They put tooling holes on the drawings.

Mr. Manson: In the early stages of the consideration of a project in his factory it was submitted to a committee comprising the chief designer and one or two of his staff and the production team; they agreed on questions of major design—types of spar —the type of formers in fuselage construction, skin riveting combinations and so on. When those matters were agreed, the methods of making the various parts were considered by a committee comprising the production research people, the process engineers and the works manager. That committee sat every fortnight, sorting out various problems. One such problem they had considered was how to produce the circular formers he had illustrated; they had solved the problem, and the job was cheap and accurate. Again, the drawing office had indicated the kind of rib required for the wing; the committee had tried out several different designs, found out which could be more easily produced and be of the required strength and submitted the results to the design office for approval.

He had nothing revolutionary to say regarding the question of new technique.

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THE THEORY OF LIMIT DESIGN APPLIED TO MAGNESIUM ALLOY AND ALUMINIUM ALLOY STRUCTURES

by

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INTRODUCTION.

THIS paper is a study of the questions: (1) Are the simplified equations and design procedure in Limit Design that have been developed for application to structural steel construction, applicable without modification to light metal structures? (2) How do the properties of these metals which are different from those of steel affect the application of the theory? Do they offer any advantages? Any disadvantages? (3) What changes in traditional design procedure are warranted? What changes are imperative?

No claim is made to a complete solution of the design problem, since each particular structure involves a thousand and one details. Only the broad fundamental philosophy is discussed here. The discussion and conclusions are supplemented with a report of a number of experiments on a few extrusions of some of the more important alloys of magnesium and of aluminium.

In view of the radical departure of the Theory of Limit Design from the well-worn and established methods of Applied Elasticity, a brief historical introduction seems justified.

When man first began to build he had no rational methods of proportioning the members of the structures that he built. He solved his construction problems largely by guesswork and the groping methods of trial and error. It is true that he did possess a certain amount of "engineering judgment," but it was only in regard to relative values, that is, he knew by instinct that of two beams of the same material, whose lengths (spans) were equal, the "stouter" one was the stronger. History[1] tells us that while certain definite relations existed among the dimensions of some structural members, as, for example, pillars, in early (up to the 14th century) building practices, there does not seem to have been any rational basis for these values. Rather they represent practices that had been found satisfactory, and were handed down from generation to generation.

The first to depart from these strictly cut and dried methods was Leonardo da Vinci.[1] He attempted among other things to solve the column problem, which was first successfully solved by Euler two and a half centuries later. The methods da Vinci employed were crude, and whatever conclusions are to be gleaned from the notes he left have not contributed much to the knowledge of the theory of strength.

After da Vinci came Galileo Galilei.[1], [2] While Galilei is most famous for his studies

and experiments in dynamics and astronomy, he did contribute to the science of strength. His was the first rational study of this science, and in his theory he presented with geometric proof a number of propositions concerning the strength of cantilevers, and of beams on two supports. Although most of his conclusions are incorrect because of wrong assumptions, he did arrive at correct results in his comparisons of relative strengths in fracture of similar beams of different dimensions. Among other things he correctly determined the shape of a cantilever beam of constant width, whose resistance to fracture against a load at the free end is uniform along its entire length. His most significant contribution lies in the fact that he was the first to consider the internal forces at the base of the cantilever. He assumed that these forces were uniformly distributed from top to bottom, and that they had a single resultant tension force acting axially at the centre of the beam (he considered beams of rectangular and circular cross sections only). The assumption is wrong, but it was a step forward.

Edmé Mariotte, [1], [3] who came some time after Galilei, made actual tests on beams to verify or disprove Galilei's propositions. He improved upon the latter's assumption by saying that the internal forces varied linearly from zero at the bottom to a maximum at the top in the cross section of a cantilever. Although he sensed that the fibres on one side of the beam lengthened while those on the other side shortened during bending (again an improvement over Galilei's assumption that the fibres were inextensible), he did not take this into account in considering the distribution of the internal forces. Later in his career Mariotte collaborated with Leibniz,[1], [3] who believed that the beam fibres were extensible and that "their resistance is in proportion to their extension." This, of course implied that Hooke's Law (1664), which had been formulated some twenty years earlier, applied to the individual fibres of the beam. This hypothesis came to be called the Mariotte-Leibniz theory.

It is noteworthy that these early investigators of the 16th and 17th centuries were interested only in the capacity resistances of beams. This was natural since they knew little, if anything, about elasticity and the elastic limit stress of materials. When, however, Robert Hooke[1], [3] gave the world the law that bears his name, the interest was shifted to the elastic behaviour of the material.

Using Hooke's Law as a basis for his work, Jacques Bernoulli[2] made his most important contribution to the bending problem by showing that the curvature of a bent beam varies directly as the strains in its fibres. This was developed later by Euler, who produced a formula equivalent to the present-day equation $1/R = M/EI$. Euler's most famous contribution to the subject is his analytical solution of the column problem, the answer to which P. van Musschenbroek[2], [3] had anticipated a few years earlier from the results of experiments on columns.

It is highly debatable whether or not Euler consciously used Hooke's Law when he attacked the problem. He was, however, emphatic in pointing out[4] that the "moment of stiffness," one of the quantities he used (equivalent to EI in present-day formulas), was a property not limited to elastic beams alone. Euler's problem was peculiar, and he could not escape the fact that he was really determining the capacity load that a column could carry, that is, the load that would induce uncontrolled deformation which for the columns in his day necessarily produced fracture.

It can be said without exaggeration that after Euler very little contribution was made to the subject of strength, insofar as engineering structures are concerned, until the early twentieth century. It is true that nineteenth century history[3] is replete with names of the great elasticians — from Charles Coulomb, who gave the first reasonably complete

analysis of the internal forces in a cantilever beam, Thomas Young, who defined Young's modulus of elasticity, Navier who is regarded as the founder of the modern theory of elastic solids, Poisson, who gave the science the famous Poisson's ratio, Clapeyron, who laid the foundation for the development of the three-moment equations for continuous beams, James Clerk-Maxwell, who first proved the special case of Reciprocal Theorem now frequently called Maxwell's Theorem, down to Barré de Saint-Venant, the greatest elastician of them all, whose fundamental assumption of transverse planes remaining planes in bending was revolutionary. In all these things the emphasis has always been on the elastic behaviour of the material, and hence the elastic behaviour of the structure only.

It was not until the dawn of the present century that men began to question the soundness of the concept, which, although it has never been explicitly stated, has nevertheless always been implied, namely, that the exceeding of the elastic limit stress at any one point in a structure, even if the structure is redundant, is tantamount to failure.

All engineers are probably agreed that such is rarely the case and that, with modern structural materials, it is not the case at all. But they are agreed also, that after the elastic limit has been exceeded the formulas of Applied Elasticity no longer hold, and that it becomes necessary to do one of two things: either to stay away from the elastic limit and take comfort in the thought that possibly these formulas apply with sufficient rigour, or, failing to do that in some cases, to adopt certain rules of thumb that years of building practice and experience have justified—rules which have absolutely nothing to do with elasticity, *e.g.*, the stress concentration around a rivet hole is completely ignored and the stress is assumed uniformly distributed around the hole. Unfortunately, neither of these things has been adopted to the complete exclusion of the other.

Instead a sort of compromise has come out of it, and the result is a sorry mixture of theory, based on Applied Elasticity, and some rules which conflict directly with that theory. Understandably, this has led to the statement that there is a conflict between theory and practice. It may be so, but practice cannot be entirely wrong, inasmuch as there are both correct and wrong practices. This does not, on the other hand, imply that the theory is wrong. It would be more proper to say that it is incomplete, since the methods of Applied Elasticity do not take into account the behaviour of structures when they are strained outside the elastic range. In the many steps and processes connected with construction, structural members or parts thereof are frequently strained beyond this range and still retain their usefulness. Thus, the question arises: Is this theory which considers only the elastic behaviour of materials and which completely ignores the ability of these materials, especially of metals, to "give" without breaking, the best possible theory on which to base structural design?

THE THEORY OF LIMIT DESIGN.

The Theory of Limit Design[5] is a theory of strength which proposes to take into account as fully as possible this "ductility" of metals, and which undertakes to explain the behaviour of structural members or entire structures when they are loaded beyond the proportional limit. It thus enables the designer to take full advantage of the outstanding properties of the materials he works with, and to obtain values very close to the limit or capacity resistances that man first set out to find. This theory, furthermore, rationalises many of the rules of thumb that successful construction has justified. In one sense it is independent of the theory of elasticity and represents an entirely different sense of values—the physical—in contrast to the purely mathematical sense of values represented by this theory of elasticity. In another, larger, sense it is a logical step forward from the concept of elasticity. One

time or another the next step had to be taken, the next question had to be asked: What happens to a structure when at some points it is stressed beyond the elastic limit.

As in most other branches of science, in Limit Design successful practice preceded rational theory. An outstanding example of this is the design of multiple rivet connections. One of the first to philosophise on the suitability or non-suitability of Hooke's Law as a basis for structural design, was Professor N. C. Kist[6] of the Universitv of Delft, Holland. He posed the question: Does the proportionality of stress and strain as a basis for design in steel construction lead to economical results? After answering this question in the negative, he laid down one of the cardinal concepts of Limit Design: In a redundant structure, it is not necessary to use the equations of elasticity to determine the redundants; it is only necessary to assume values for them, any assumptions at all but preferably the most advantageous ones, provided such assumptions are compatible with the conditions of equilibrium. *In the judicious choice of these assumptions lies the key to the successful application of the Theory of Limit Design.*

Kist thought only in general terms. His published articles do not say whether he made tests in support of his philosophy. As far as can be ascertained the earliest published tests that have any bearing on Limit Design are those performed by H. F. Moore[7] in 1913. Moore tested simple steel beams only, and the full significance of Kist's principle was not realised. On the other hand, the tests on continuous steel beams made by Maier-Leibnitz[8] in 1928 proved the correctness of Kist's contention. Furthermore, they provided a guide in the choice of those assumptions for the redundants.

During the time of Kist and the early pioneers there were developed no simple formulas for Limit Design comparable to those for Applied Elasticity. In America at least, it has remained for Professor J. A. Van den Broek of the University of Michigan to rationalise, systematise, and expand the theory. Indeed, the designation "Limit Design"[5] is his. His most outstanding contribution is his emphasis on the fact (which many still refuse to admit) that in all construction, antiquated or modern, the elastic limit stress has never been a true criterion of strength. The true and only criterion has always been deformation. Stress comes in only as a secondary item, when the loads or load carrying capacities are computed. This is especially true in redundant structures.

In applying the theory to steel structures Van den Broek offers dictum 3 as follows: "When in a well-designed and especially properly detailed n-fold redundant structure n redundant members are stressed to their elastic limit or up to their critical buckling loads, the deformations involved are of the order of magnitude of elastic deformations until an $(n+1)$th member reaches its elastic or its critical buckling capacity."[5]

Thus, while Kist and Van den Broek are both right, they differ in approach. Kist was concerned first and last with equilibrium. He knew (and correctly) that if he assumed any values for the redundants and then designed them according to those assumptions, he could determine from statics what the remaining determinate values would be. Van den Broek, on the other hand, wants to know more about what actually happens to the structure as the loads on it are increased until deformations become excessive. In knowing this behaviour he is in a better position than Kist was in making the most advantageous assumptions for the redundants.

APPLICATION TO STEEL STRUCTURES.

Modern structural metals may be divided into two groups: ductile and brittle. Strictly speaking there is none among these metals that is completely brittle, like glass. It is always possible to produce some permanent set, be it ever so small, in every metal. Probably the one which approaches glass

closest in brittleness is cast iron. On the other extreme there is at least one metal which exhibits to a considerable extent perfectly ductile behaviour. This is mild or hot rolled steel. The other structural metals, notably the light metals, fall between these two extremes.

The early portion of the stress-strain curve of structural steel, in both tension and compression, is represented in Fig. (a). The sharp knee is probably a simplification, this region being one of instability.[9] The significant fact is that the horizontal portion extends to a value of the strain, *e*, sometimes up to twenty times the elastic limit strain, here taken for all practical purposes as equal to the proportional limit strain.

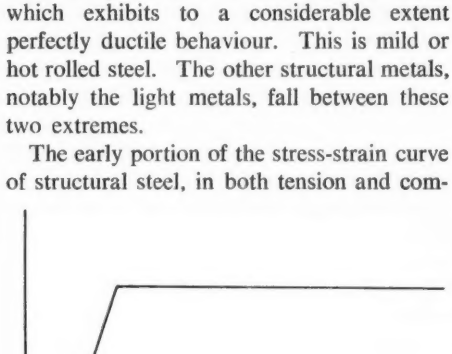

Fig. a.

This remarkable property of steel enables structural members made of it to behave under load in a simple manner which may be summed up thus: In the elastic range the load and the corresponding deformation vary linearly; after the elastic range there is a transition into a sharply defined condition in which the deformation increases without any appreciable increase in the load. This condition is so clear cut that it is a logical choice for a limit. Expressed differently, this means that the load-deformation diagram for any member of a steel structure is qualitatively the same as the stress-strain curve, with or without the knee, but with the same considerable "flat" portion. What actually happens in the transition is not of primary concern here. The important fact is that a member made of structural steel is capable of developing its particular limit performance. The application of the Theory of Limit Design to steel structures is based on the implied assumption that some particular member, having reached its limiting condition, *continues* to function in this limiting condition and to contribute a *constant* resistance to increasing load until as many other members as can "catch up" finally do catch up (Van den Broek's dictum 3).

In a beam this limiting condition is associated with a limit moment which is peculiar to the particular form of the cross section of the beam and which depends on the yield point of the steel of which it is made. A section which has reached such a condition is sometimes referred to as a "yield hinge." This implies that, if such a section is part of a redundant beam, it will act much as a hinge would, with the difference that instead of transmitting a zero bending moment it will transmit a constant bending moment. The limiting condition for the entire beam is reached when as many sections as can "equalise" their bending moments are developing simultaneously the same resisting moment.

The peculiar behaviour of a beam section just described leads to an extremely simple solution of the redundant beam problem. Kist's principle says: Make the most advantageous assumption for the redundants. Obviously the most advantageous assumption for any one section of a beam is its own limit resisting moment. Van den Broek's dictum 3, in effect, says: Assume as many equalised bending moments as there are redundants plus one, for it is only then that the deformations of the beam cease to be of the order of magnitude of elastic deformations.

In any one span of any beam there cannot possibly be more than two redundants. This

follows from the fact that the conditions of equilibrium can yield only two independent equations—if it is assumed that there are no axial forces and no twisting moments—and that there can be at most only four restraints: two shearing forces and two bending moments. In other words, n in Van den Broek's dictum 3 cannot be greater than 2. In any continuous beam n equals 2 for an interior span and 1 for an exterior span, if for the exterior span the exterior support is considered a simple one.

The following rule is now offered as a guide in the application of Limit Design to continuous beams: *For any one span of any continuous beam, construct the bending moment diagram on the basis that this span is considered as a simple beam. On this diagram superimpose on the same side of the reference line the bending moment diagram (a straight line) due to the extra restraint, or restraints. Adjust this line until two equal moment intercepts for an exterior span, or three equal moment intercepts for an interior span, are obtained which are the lowest possible values for any number of combinations, but which are the highest possible values in that particular combination. These particular sections are the ones in which the equalised bending moments are to be assumed. The remaining quantities in the system can then be determined from the equations of statics.*

This rule is a logical consequence of the fact that the variation of the bending moments, as the loads are increased from zero, is continuous; therefore, the distribution of these bending moments must pass through a combination of minimum values before a combination of maximum values is reached. The usual load combinations encountered in practice should present no difficulties. However, a system may arise in which it is not obvious where to assume the equalised moments. The following simple, though somewhat far-fetched example, will serve to illustrate this rule.

Figure (b) represents the exterior span of a continuous beam carrying the loads

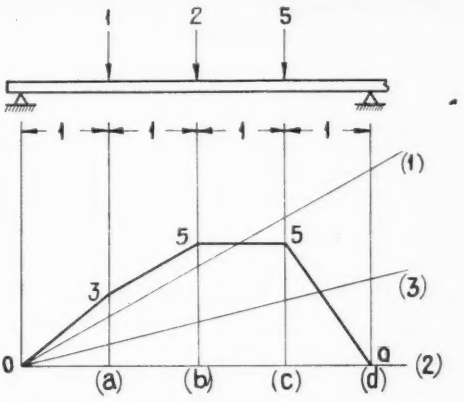

Fig. b.

indicated. The bending moment diagram is constructed with the beam considered as simply supported. The moment ordinates, from left to right, are 0, 3, 5, 5, and 0 units. Assuming the left end of the continuous beam to be simply supported, the bending moment diagram, due to the added restraining moment at the right support, is represented by an inclined straight line starting from zero at the left end. There are three possible positions for this line, each of which yields two equal moment intercepts. They are marked (1), (2) and (3). Position (1) yields two equal moments, one at (a) and one at (b), but these are not the greatest values in this particular combination since the moment at (d) is greater than either. Position (2) gives two equal intercepts, one at (b) and one at (c), but these values are higher than those at (b) and at (d) given by position (3). Therefore, (b) and (d) are the sections in which equal bending moments are assumed, and the design proceeds from there.

In the application of the theory to framed structures, in which compression and tension members are involved, it must be pointed out that the stipulation of a limiting condition for the entire structure is contingent upon the ability of the compression members to behave like long columns subject to centrally applied

loads (pin connections). The load-deformation curves of long steel columns resemble the stress-strain curve,[10] *i.e.*, immediately after a long column buckles it continues to carry practically 100 per cent. of its buckling load, and carries this load for a considerable extent of its deformation in the direction of the load (see Fig. 16 of reference 10). The longer the column is, the longer is the extent to which it does this. This "ductile" behaviour of a long column thus permits a buckled member to behave in the manner described earlier. This is the basic philosophy that has governed the design of transmission towers, a unique field of structural engineering wherein Limit Design has found its freest expression and in which its conscious application has been crowned with glowing success.[11]

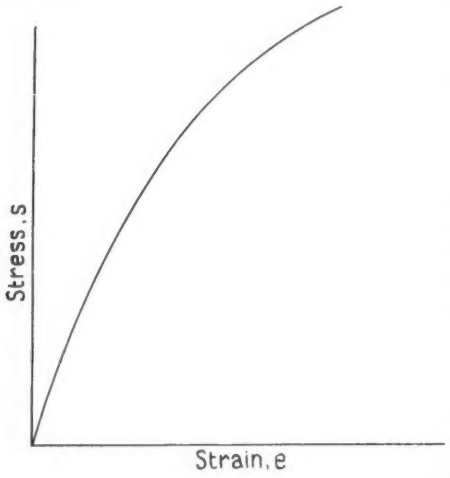

Fig. c.

If the columns are not long columns and the loads are not centrally applied, as is usually the case in practice, then the exact determination of the limiting conditions for such members will have to await further developments in column research. In the meantime, assumptions for the load carrying capacities of these short non-pin connected columns must continue to be based on empirical formulas and intelligent guesswork.

As for the connections in framed structures, if there is any fixity, it can at best be estimated only from the stiffness of the members connected. The extent to which the assumptions for the redundants are actually realised in the limit depends on the accuracy of such an estimate. Exploring further the implications of the theory of Limit Design, the conclusion is that a structural member is capable of ductile behaviour only to the extent to which the connections will allow such behaviour. Hence, the guiding principle in designing connections is: *Connections should be designed "not only so as to develop as nearly as possible the full strength of the members, but so as to develop the full ductility of the members as well."*[12]

APPLICATION TO MAGNESIUM ALLOY AND ALUMINIUM ALLOY STRUCTURES.

The light metal alloys are neither completely brittle nor completely ductile. Like steel they are capable of almost perfectly elastic behaviour, but when stressed past the elastic limit the relation between load and corresponding deformation is entirely different from that in structural steel. Qualitatively the stress-strain curve in tension as well as in compression, with a few exceptions, is generally as shown in Fig. (c).

This characteristic immediately brings out one significant fact, that excessive deformation does not begin at any one point in the stress-strain diagram. What is true of the stress-strain curve necessarily holds also for any one load-deformation curve of members (except columns) made of these metals. The conclusion is inevitable that some value of deformation must be decided upon arbitrarily as a criterion of permissible deformation in determining the range of usefulness of structures made of the alloys of magnesium and of aluminium.

The limiting condition for any light metal structural member must be defined, taking into consideration either the total deformation it may suffer during service, or the total

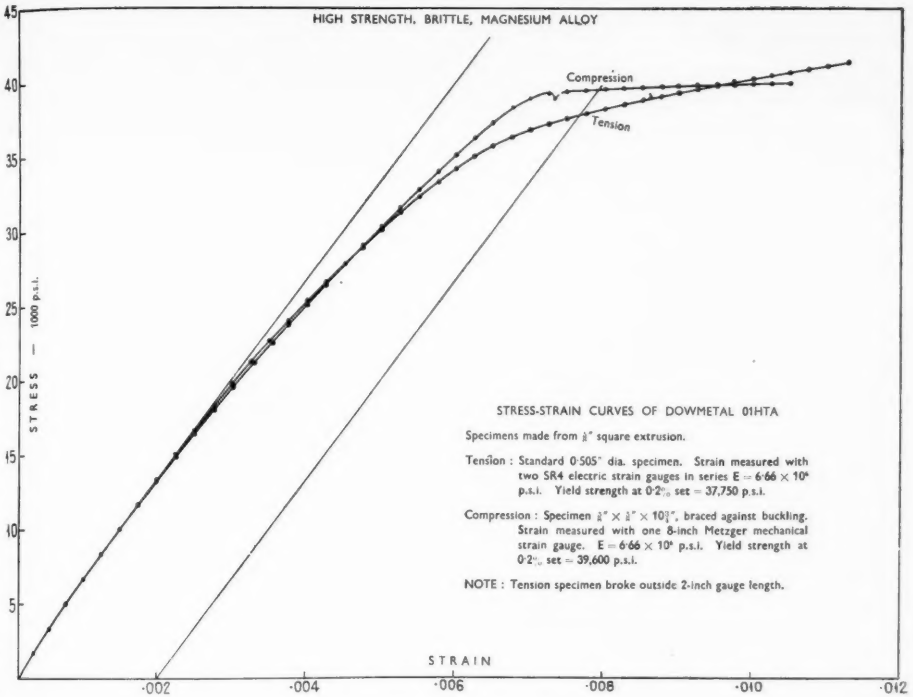
HIGH STRENGTH, BRITTLE, MAGNESIUM ALLOY
Compression
Tension
STRESS — 1000 p.s.i.
STRAIN
·002
·004
·006
·008
·010
·012
STRESS-STRAIN CURVES OF DOWMETAL 01HTA
Specimens made from ⅜" square extrusion.
Tension : Standard 0·505" dia. specimen. Strain measured with two SR4 electric strain gauges in series E = 6·66 × 10⁶ p.s.i. Yield strength at 0·2% set = 37,750 p.s.i.
Compression : Specimen ⅜" × ⅜" × 10¾", braced against buckling. Strain measured with one 8-inch Metzger mechanical strain gauge. E = 6·66 × 10⁶ p.s.i. Yield strength at 0·2% set = 39,600 p.s.i.
NOTE : Tension specimen broke outside 2-inch gauge length.

Fig. 1.

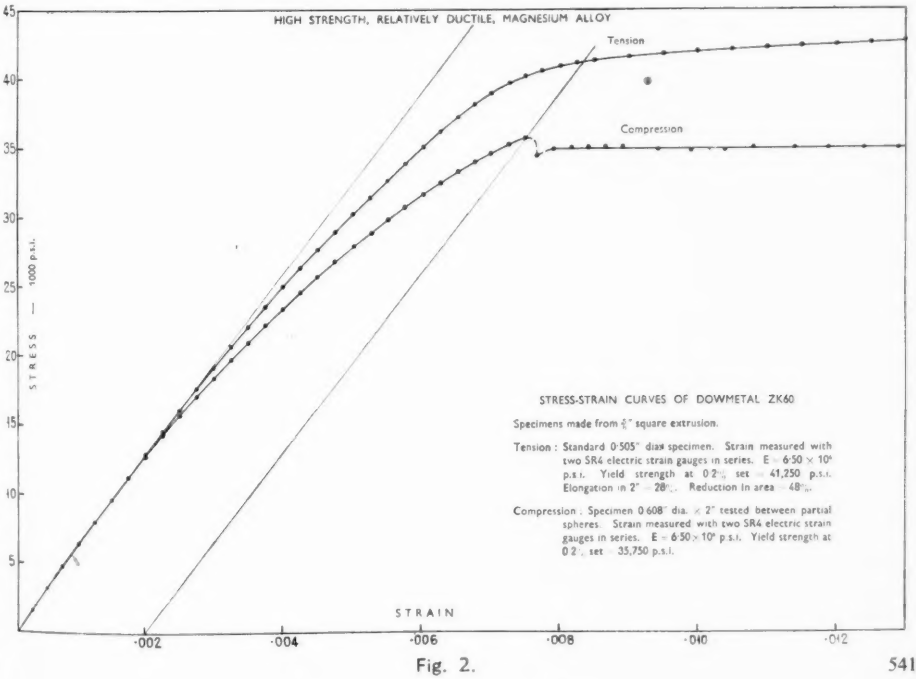
HIGH STRENGTH, RELATIVELY DUCTILE, MAGNESIUM ALLOY
Tension
Compression
STRESS — 1000 p.s.i.
STRAIN
·002
·004
·006
·008
·010
·012
STRESS-STRAIN CURVES OF DOWMETAL ZK60
Specimens made from ½" square extrusion.
Tension : Standard 0·505" diam specimen. Strain measured with two SR4 electric strain gauges in series. E = 6·50 × 10⁶ p.s.i. Yield strength at 0·2% set = 41,250 p.s.i. Elongation in 2" = 28%. Reduction in area = 48%.
Compression : Specimen 0·608" dia. × 2" tested between partial spheres. Strain measured with two SR4 electric strain gauges in series. E = 6·50 × 10⁶ p.s.i. Yield strength at 0·2% set = 35,750 p.s.i.

Fig. 2.

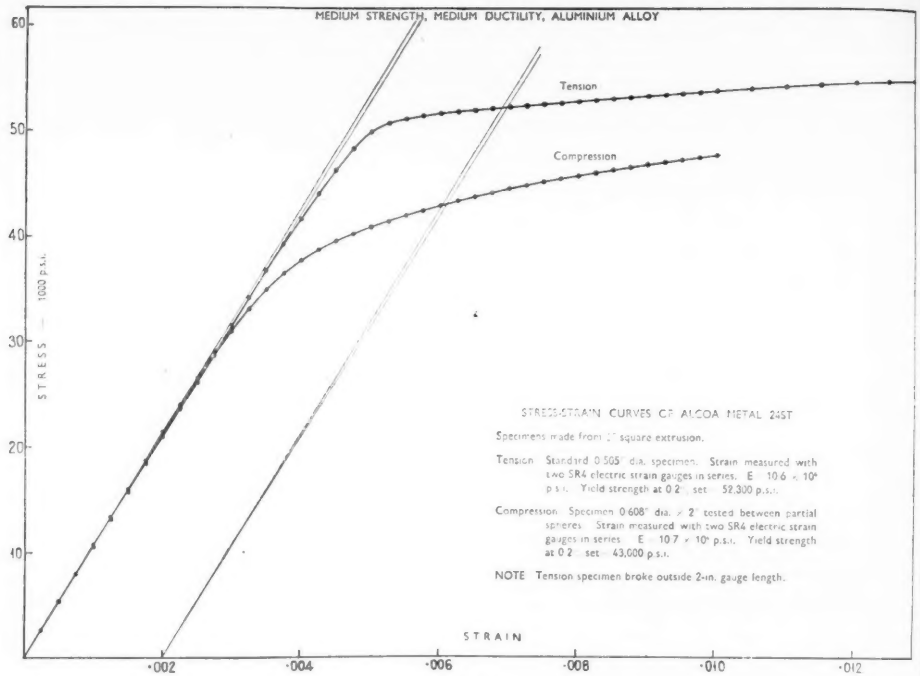
MEDIUM STRENGTH, MEDIUM DUCTILITY, ALUMINIUM ALLOY
Tension
Compression
STRESS — 1000 p.s.i.
STRAIN
·002
·004
·006
·008
·010
·012
STRESS-STRAIN CURVES OF ALCOA METAL 24ST
Specimens made from 2" square extrusion.
Tension. Standard 0·505" dia. specimen. Strain measured with two SR4 electric strain gauges in series. E = 10·6 × 10⁶ p.s.i. Yield strength at 0·2% set = 52,300 p.s.i.
Compression. Specimen 0·608" dia. × 2" tested between partial spheres. Strain measured with two SR4 electric strain gauges in series. E = 10·7 × 10⁶ p.s.i. Yield strength at 0·2% set = 43,600 p.s.i.
NOTE. Tension specimen broke outside 2-in. gauge length.

Fig. 3.

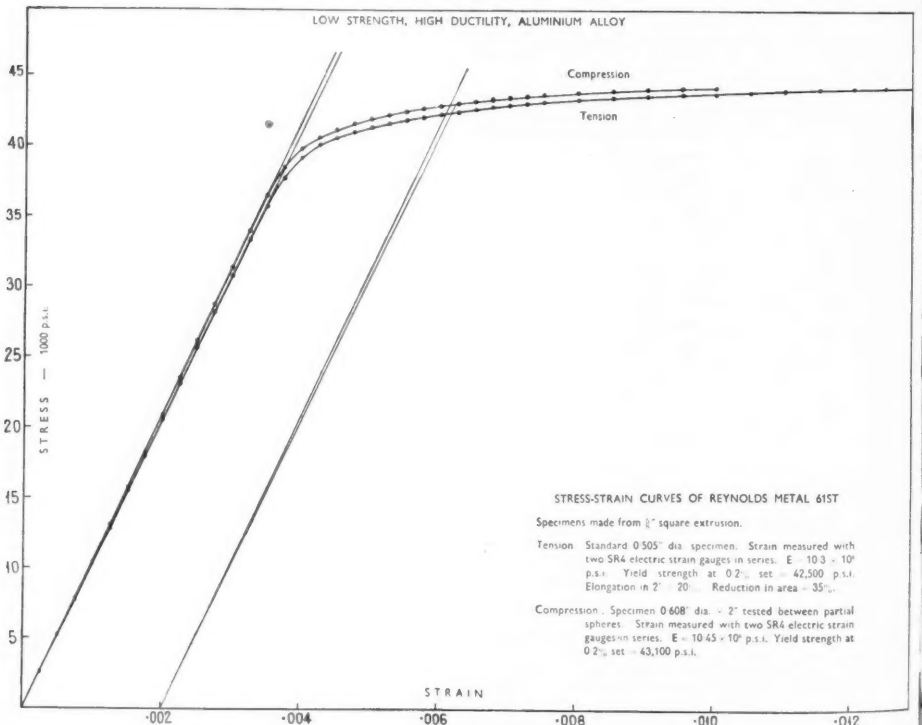
LOW STRENGTH, HIGH DUCTILITY, ALUMINIUM ALLOY
Compression
Tension
STRESS — 1000 p.s.i.
STRAIN
·002
·004
·006
·008
·010
·012
STRESS-STRAIN CURVES OF REYNOLDS METAL 61ST
Specimens made from ½" square extrusion.
Tension. Standard 0·505" dia. specimen. Strain measured with two SR4 electric strain gauges in series. E = 10·3 × 10⁶ p.s.i. Yield strength at 0·2% set = 42,500 p.s.i. Elongation in 2" = 20%. Reduction in area = 35%.
Compression. Specimen 0·608" dia. × 2" tested between partial spheres. Strain measured with two SR4 electric strain gauges in series. E = 10·45 × 10⁶ p.s.i. Yield strength at 0·2% set = 43,100 p.s.i.

Fig. 4.

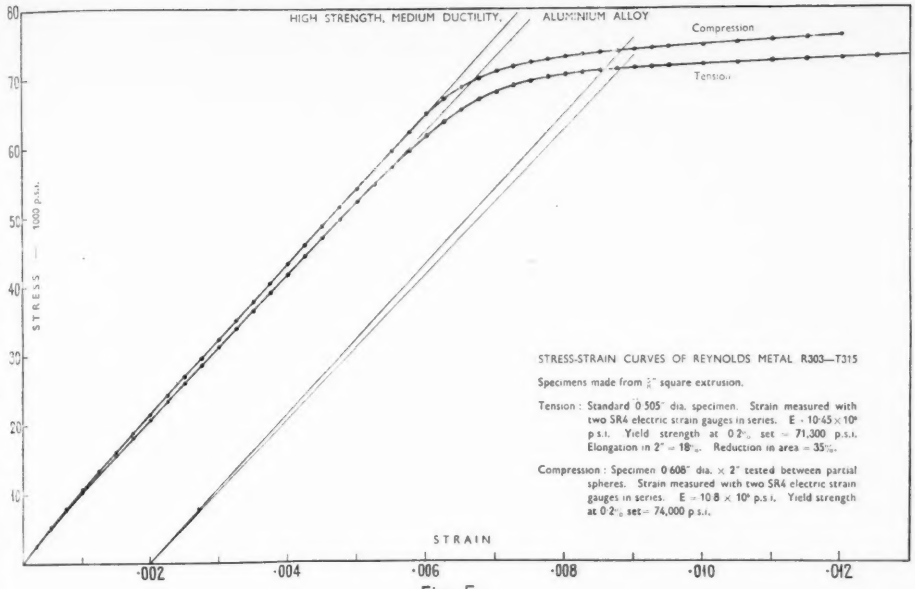
HIGH STRENGTH, MEDIUM DUCTILITY, ALUMINIUM ALLOY
Compression
Tension
STRESS — 1000 p.s.i.
STRAIN
·002
·004
·006
·008
·010
·012
STRESS-STRAIN CURVES OF REYNOLDS METAL R303—T315
Specimens made from ½" square extrusion.
Tension : Standard 0·505" dia. specimen. Strain measured with two SR4 electric strain gauges in series. E = 10·45 × 10⁶ p.s.i. Yield strength at 0·2% set = 71,300 p.s.i. Elongation in 2" = 18%. Reduction in area = 35%.
Compression : Specimen 0·606" dia. × 2" tested between partial spheres. Strain measured with two SR4 electric strain gauges in series. E = 10·8 × 10⁶ p.s.i. Yield strength at 0·2% set = 74,000 p.s.i.

Fig. 5.

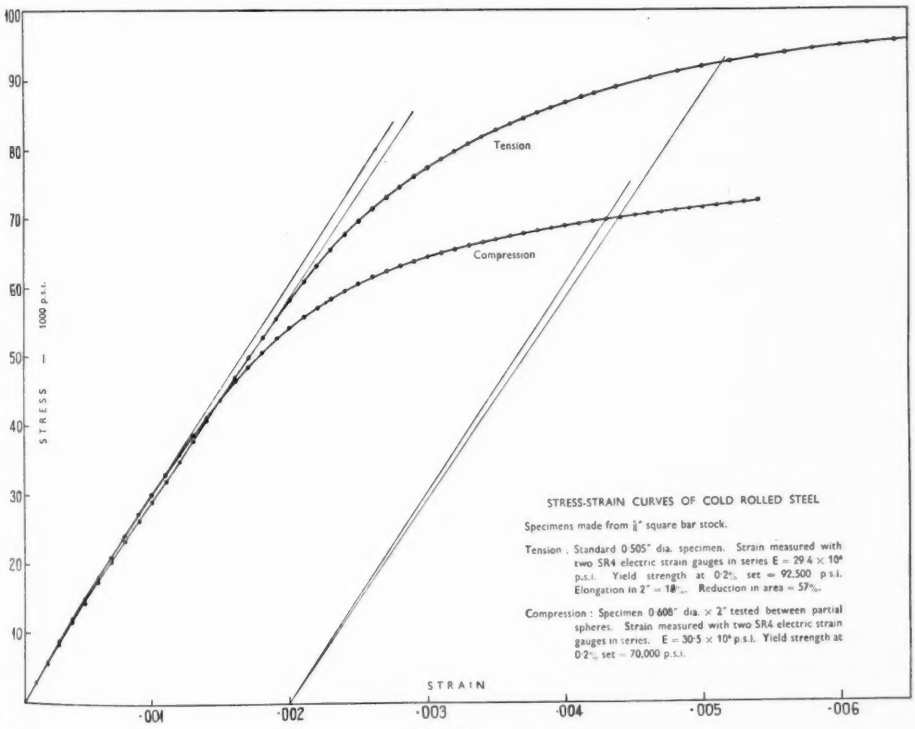
Tension
Compression
STRESS — 1000 p.s.i.
STRAIN
·001
·002
·003
·004
·005
·006
STRESS-STRAIN CURVES OF COLD ROLLED STEEL
Specimens made from ½" square bar stock.
Tension : Standard 0·505" dia. specimen. Strain measured with two SR4 electric strain gauges in series E = 29·4 × 10⁶ p.s.i. Yield strength at 0·2% set = 92,500 p.s.i. Elongation in 2" = 18%. Reduction in area = 57%.
Compression : Specimen 0·606" dia. × 2" tested between partial spheres. Strain measured with two SR4 electric strain gauges in series. E = 30·5 × 10⁶ p.s.i. Yield strength at 0·2% set = 70,000 p.s.i.

Fig. 6.

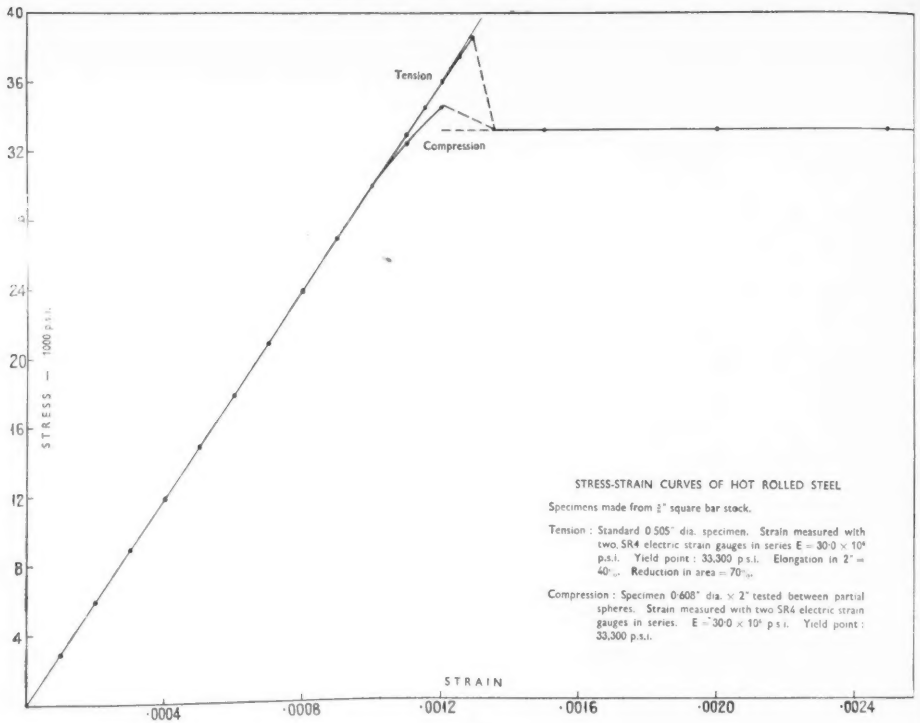
40
36
32
24
20
16
12
8
4
STRESS — 1000 p.s.i.
Tension
Compression
STRESS-STRAIN CURVES OF HOT ROLLED STEEL
Specimens made from ⅝" square bar stock.
Tension : Standard 0·505" dia. specimen. Strain measured with two SR4 electric strain gauges in series E = 30·0 × 10⁶ p.s.i. Yield point : 33,300 p.s.i. Elongation in 2" = 40%. Reduction in area = 70%.
Compression : Specimen 0·608" dia. × 2" tested between partial spheres. Strain measured with two SR4 electric strain gauges in series. E = 30·0 × 10⁶ p.s.i. Yield point : 33,300 p.s.i.
STRAIN
·0004
·0008
·0012
·0016
·0020
·0024

Fig. 7.

permanent deformation it may be allowed to retain. Any way in which this condition may be defined, the arbitrary approach is inescapable. Thus the first glaring difference between the properties of the light metals and those of steel is recognised. In structural steel members there is defined beyond any doubt a condition in which deformations become uncontrolled *without the threat of fracture being necessarily involved*. The load or resisting moment corresponding to such a condition may be thought of as a property inherent in the particular section or member. This represents a service which the member does not necessarily have to perform, but which it is potentially capable of performing if called upon to do so.

On the other hand, in the alloys of magnesium and of aluminium there is no such well-defined point. Deformations in members made of such metals become excessive only when they exceed some value that will have to be agreed upon in advance, and in no sense do these deformations become "uncontrolled" except at, or very near, fracture. Therefore, the limit loads, or limit moments, likewise have to be arbitrarily defined. The fact has to be faced that the very nature of the stress-strain characteristics of these metals precludes any exact determination of limit loads, mathematical or experimental. In the laboratory an individual isolated member could be so tested as to develop its ultimate performance, but such performance would be difficult if not impossible to evaluate in terms of actual service conditions when such a member is an integral part of a larger structure.

The presence or absence of such a well-defined condition of yielding, however, is a matter of only secondary importance in design. The considerations on which light

must be shed really are: — What assumptions may be made for the strength of structural members of magnesium alloys and aluminium alloys. For any one such assumption how much more or less is the margin of safety in terms of the probable potential load carrying capacity To throw light on these matters the following propositions are offered. Tests to substantiate these propositions will be discussed later.

First, the fact that, insofar as primary failures are concerned, the use of the elastic limit stress as a criterion of limiting conditions is no longer indicated in redundant steel structures, means that it is even less indicated in redundant light metal structures. Second, the very nature of the load-deformation characteristics of the alloys of magnesium and of aluminium allows the application of Kist's principle to an even greater advantage than does steel. This second proposition simply means that while the presence of the well-defined yield condition may be desirable for the sake of having a clear cut limiting state on which to base working values (loads, and so on), its absence actually constitutes an advantage in that relatively higher loads can be carried by the redundant structure because of the *continuing* ability of the structural members to develop *increasing* resistances.

In evaluating the strength of structures it is necessary to have a suitable yardstick. In view of the fact that no hard and fast limits for allowable deformations are at hand, the most logical thing to do is to compare the deformations in a redundant system with the deformations in a statically determinate system of similar dimensions under loads that are identically applied. Such a choice is natural since the present-day concept of elastic limit stresses and working stresses is a carry over from the days of statically determinate structures. The proposed yardstick is a suitable statically determinate system subject to a certain combination of loads. The reason for this is that if the maximum elastic deformations of a statically determinate system are acceptable, then deformations of the same order of magnitude in a similar redundant system under similar loads should likewise be acceptable. In the case of beams the deformations in a redundant beam which, except for the redundant restraint or restraints, is identical to a simple beam, will be compared to the deformations in the latter when the two beams are subjected to an identical system of loading.

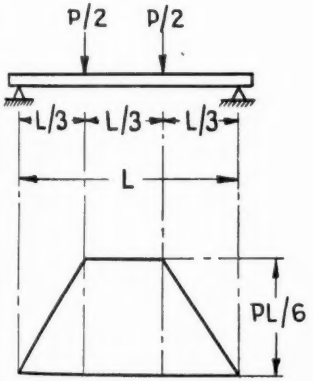

Fig. d.

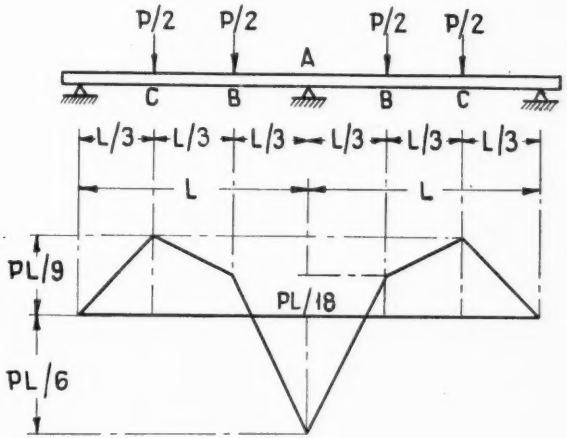

Fig. e.

EXPERIMENTS: SERIES A AND SERIES B.

There are many possible combinations of simple beams and of the corresponding redundant beams which are all easily set up in the laboratory. The combination which makes the strongest appeal is that shown in Figs. (d) and (e). Fig. (d) represents a simple beam on two supports carrying two loads at its third points. Fig. (e) represents a beam on three supports at the same level whose two spans are equal to the span of the simple beam. This second beam carries two loads in each span also applied at the third points.

This set-up appeals for two reasons. First, complete fixity, which in the classroom is just an academic abstraction, is beautifully and conveniently realised in the symmetry of the redundant beam, *i.e.*, one half of this beam may be considered as a beam which is completely fixed at one end and simply supported at the other end. Second, within the elastic range the maximum bending moment in the

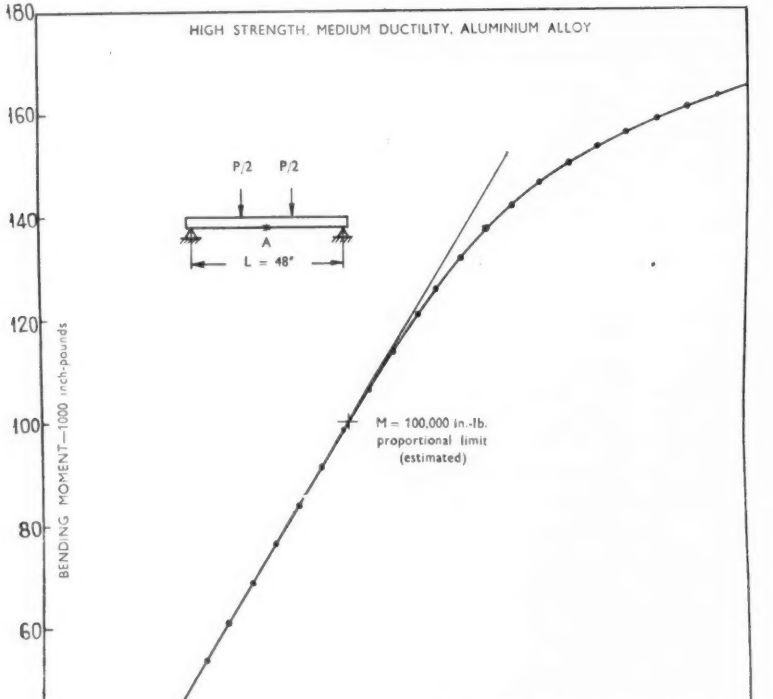

Fig. 8.

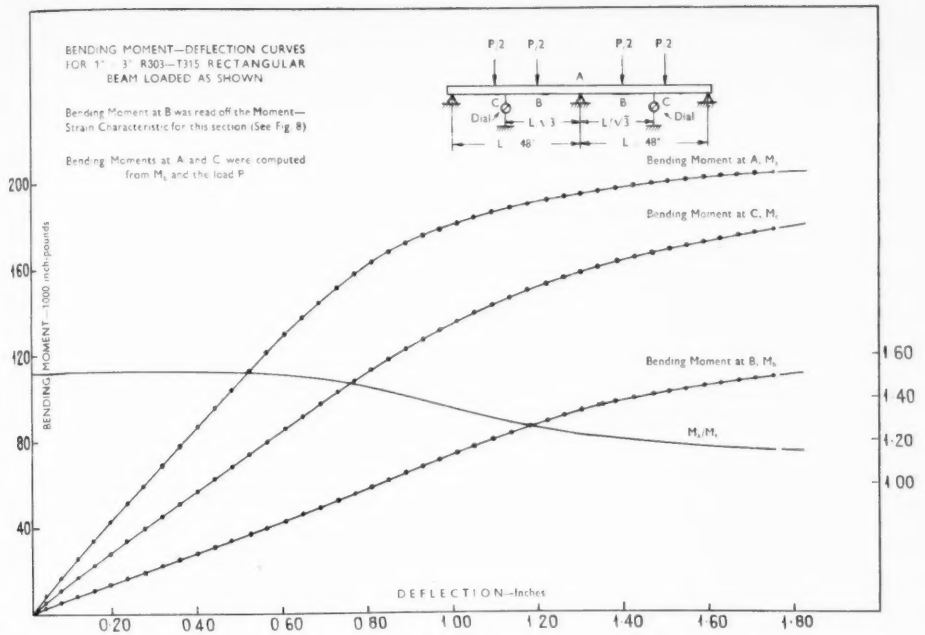

Fig. 9.

redundant beam is the same as the maximum bending moment in the simple beam, both equal to $PL/6$. Thus, according to the elastic limit stress criterion of strength, both redundant and statically determinate beams should be of the same strength. The test records manifest at a glance the error involved in this criterion.

SERIES *A* (Figs. 8 to 17).

The object is threefold. First, to demonstrate the property of the light metals, described earlier, which makes the load-deformation diagram of a light metal structural element (in this case a beam) similar to the stress-strain curve. Second, to prove that because of this property the redundant-plus-one sections in a beam never equalise moments within reasonable limits of deformation even for low initial ratios of the bending moments, that is, ratios of these moments in the elastic range as given by the equations of Applied Elasticity. Third, to verify experimentally Van den Broek's dictum 3.

The following extrusions were tested: 1 in. × 3 in. Reynolds aluminium alloy R303-T315 rectangular section, $L=48$ in. (see Figs. (d) and (e)); 1 in. × 3 in. Reynolds aluminium alloy 61ST rectangular section, $L=48$ in.; $\frac{5}{8}$ in. × $\frac{5}{8}$ in. Dowmetal magnesium alloy ZK60 square section, $L=12.5$ in. The rectangular bars were tested in the 200,000 lb. Rhiele universal testing machine of the Materials Testing Laboratory of the University of Michigan. The square bars were tested in the 72,000 lb. Amsler universal hydraulic testing machine. The deflections were measured with Federal dial gauges. The surface strains were measured with SR4 electric strain gauges (See Plate I).

The following readings were taken:— the total load P_1 for the simple beam, the deflection at the centre, and the extreme fibre strain in tension at the centre also; the total load $2P_2$ for the redundant beam, the deflections

at two symmetrical points whose distance from the centre support was $L/\sqrt{3}$ (the deflection is maximum at these two points within the elastic range), and the extreme fibre strains in tension at the sections B.

The following curves were plotted:— a characteristic curve showing the variation of the resisting moment with the extreme fibre strain in the simple beam (Figs. 8, 11 and 15); a series of curves showing the variation of the bending moments at the three sections A, B and C as well as the variation of the ratio M_a/M_c with the deflection in the redundant beam (Figs. 9, 12 and 16); a load-deflection curve for the simple beam and one for the redundant beam (Figs. 10, 13 and 17). The deflections for the redundant beam are the averages of the two dial readings. The moment (M_b) at B was read off the moment-fibre strain characteristic curve for mean

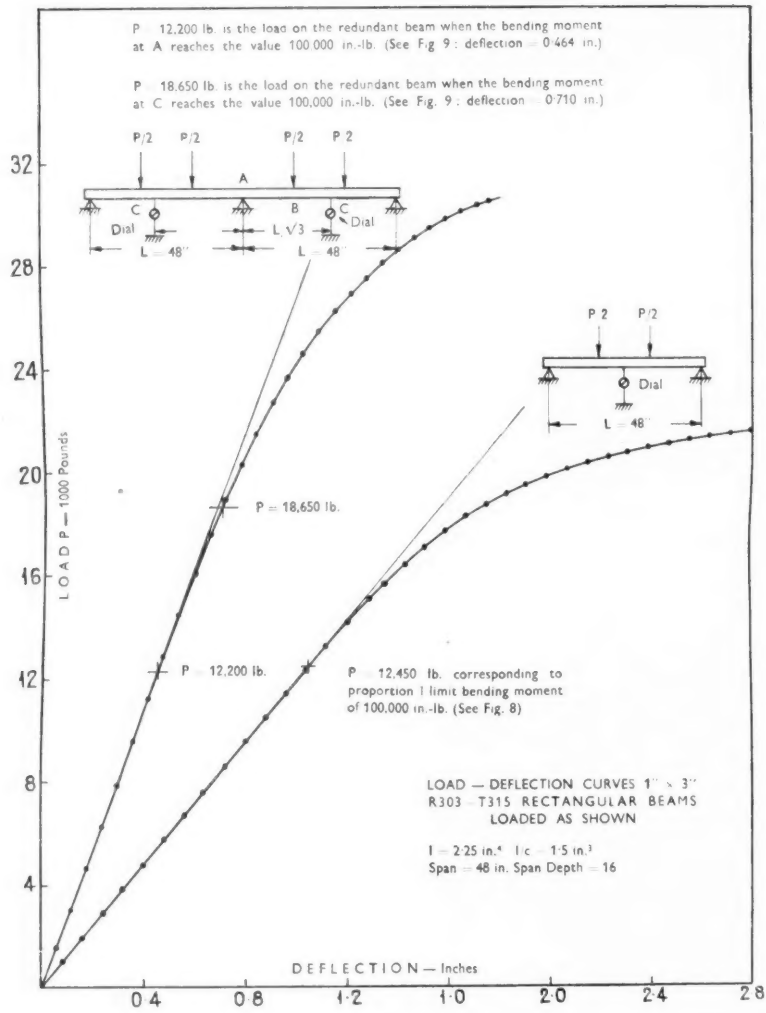
P = 12,200 lb. is the load on the redundant beam when the bending moment at A reaches the value 100,000 in.-lb. (See Fig. 9 : deflection = 0·464 in.)
P = 18,650 lb. is the load on the redundant beam when the bending moment at C reaches the value 100,000 in.-lb. (See Fig. 9 : deflection = 0·710 in.)
P/2 P/2 P/2 P/2
A
B
C
C
Dial
Dial
L√3
L = 48"
L = 48"
P/2 P/2
Dial
L = 48"
P = 18,650 lb.
P = 12,200 lb.
P = 12,450 lb. corresponding to proportion l limit bending moment of 100,000 in.-lb. (See Fig. 8)
LOAD — DEFLECTION CURVES 1" × 3" R303 — T315 RECTANGULAR BEAMS LOADED AS SHOWN
I = 2·25 in.⁴ I·c = 1·5 in.³
Span = 48 in. Span Depth = 16
LOAD P — 1000 Pounds
DEFLECTION — Inches
32
28
24
20
16
12
8
4
0·4
0·8
1·2
1·0
2·0
2·4
2·8

Fig. 10.

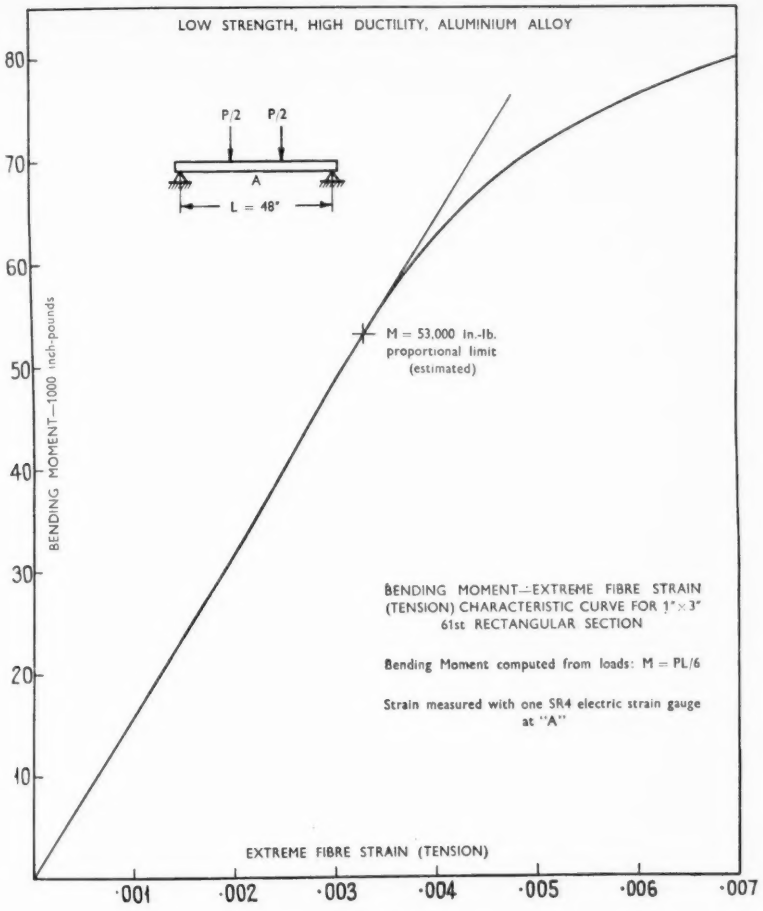

Fig. 11.

values of the strain as given by the two SR4 electric gauges at the sections B, while the moments M_a and M_c were computed from M_b, the known load P, and the equations of statics.

INTERPRETATION OF THE RESULTS.

First: Figs. 8, 11, 15, 10, 13 and 17 all show that the load-deformation (or the moment-fibre strain) curves for these alloys are similar to the stress-strain curves, which are given in Figs. 5, 4 and 2. All these curves, with the exception of the compression stress-strain curve of Dowmetal ZK60 (Fig. 2) have no "knees." This detail, as also that of Dowmetal 01HTA (Fig. 1), has significance only in explaining the shift of the neutral axis of the beam while bending past the elastic limit. This is not of primary concern here.

Second: From Figs. 9, 12 and 16 it is clear that in spite of the low initial ratio of M_a to M_c (which analytically should be $PL/6 \div PL/9 = 1.5$, but which experimentally came out to be 1.52, 1.53 and 1.41, respectively, for the three tests), M_c does not quite catch up with M_a; and although the curve for M_a/M_c does show a tendency to be asymptotic to the horizontal line through

1.00, such an equalisation of moments obviously would occur only at prohibitive deflections. The necessity for an arbitrary definition of limiting conditions should be perfectly evident from these curves. Fig. 14 shows a comparison of the M_n/M_c curves of the R303-T315 and 61ST aluminium alloy sections. They tend to the same value. The fact that the 61ST curve dips sooner to a lower level follows from the lower strength of this alloy. Compare the stress-strain curves Figs. 5 and 4.

Third: Figs. 10, 13 and 17 each has marked on it three points—one for the simple beam and two for the redundant beam. The point on the simple beam curve corresponds to the load when the centre section first develops the proportional limit resisting moment, which is determined from the moment-fibre strain characteristic. The lower point on the redundant beam curve corresponds to the reaching of the proportional limit bending moment at section A (redundant section, $n=1$), while the upper point corresponds to the reaching of this bending moment at the next critical section, $C(n+1=2)$.

It is noteworthy that even under the loads corresponding to this second point the deformations in the redundant systems are still of the order of magnitude of the elastic deformations, *i.e.*, the deviation from the original straight line is still very small, and there is definitely no tendency to "run away." What is more striking is the fact that under these "limit" loads the deformations in the redundant systems are still much smaller than the proportional limit deflections in the simple beams!

The implication is that Van den Broek's dictum 3 applies with even greater force to light metal structures than it does to structures of mild steel.

SERIES B (Figs. 18 to 23).

The object is two-fold. First, to show that the elastic limit stress is an extremely inadequate criterion of the strength of a redundant structure and this is especially so

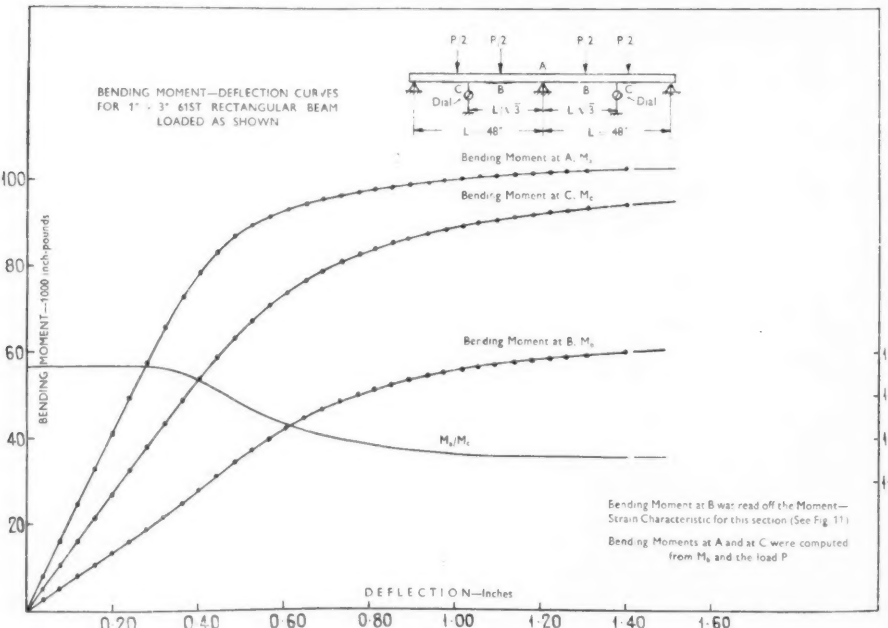

Fig. 12.

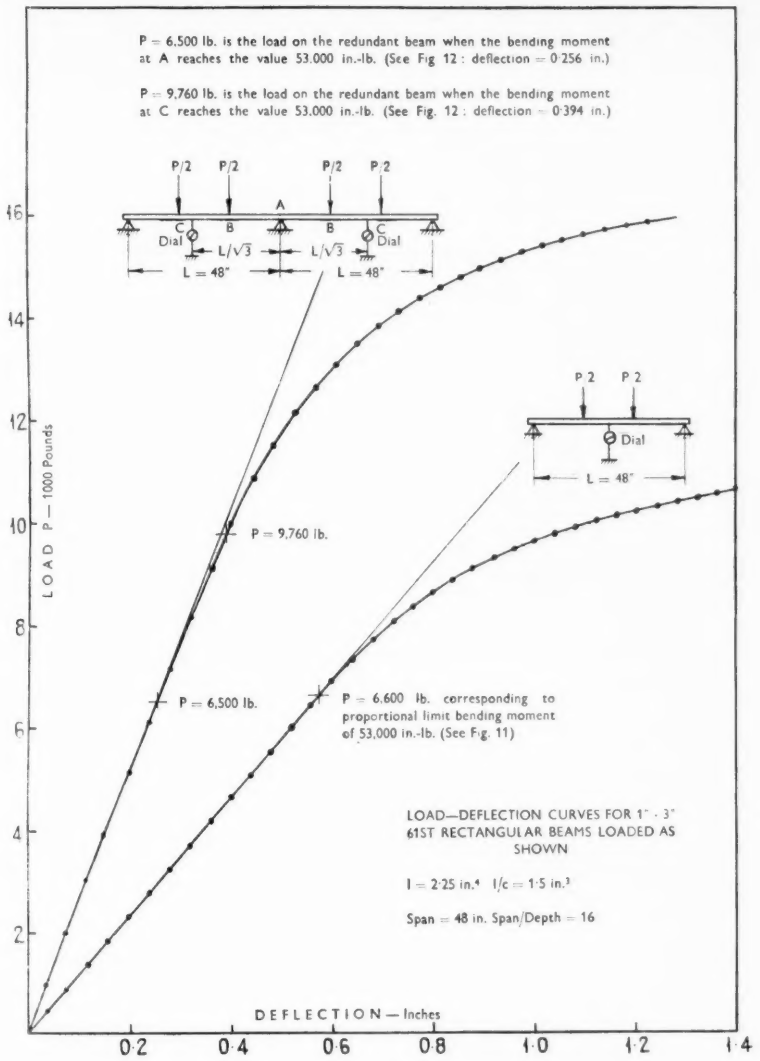

Fig. 13.

in the case of structures made of the alloys of magnesium and of aluminium. Second, to demonstrate the truth of the statement made earlier that the absence of the well-defined condition of yielding in the light metals actually constitutes an advantage, in that relatively much higher loads can be carried by redundant structures made of these metals (as compared to similar statically determinate structures) than can be carried by redundant structures of mild steel (as compared to similar statically determinate structures).

The following extrusions were tested:— Dowmetal magnesium alloy ZK60, Dowmetal magnesium alloy 01HTA, Alcoa aluminium alloy 24ST, Reynolds aluminium alloy 61ST,

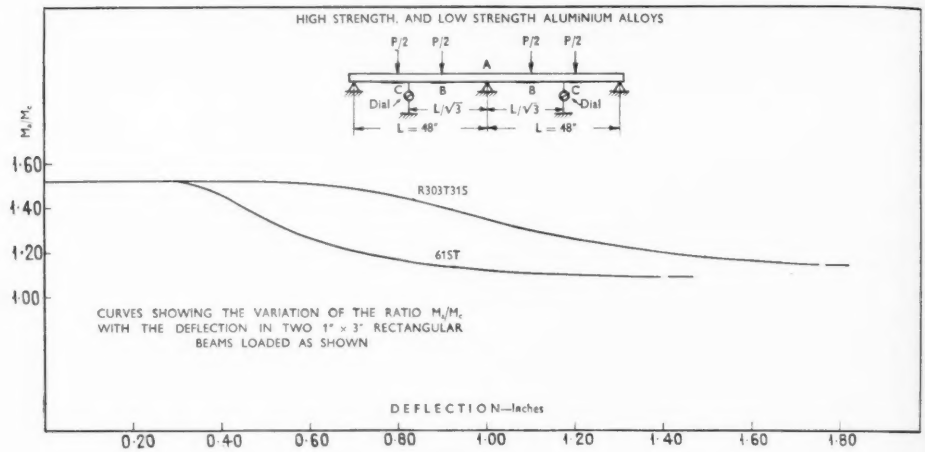

Fig. 14.

Reynolds aluminium alloy R303-T315, and bars (from stock) of cold rolled steel and hot rolled steel. All bars were $\frac{5}{8}$ in. square and all spans were equal, $L = 12.5$ in., giving a span-to-depth ratio of 20 (see Figs. (d) and (e)). All tests were run in the Amsler universal hydraulic testing machine with the 7,200 lb. scale. Deflections were measured with Federal dial gauges.

The following readings were taken:—total load P_1 for the simple beams, deflection at the centre; total load $2P_2$ for the redundant

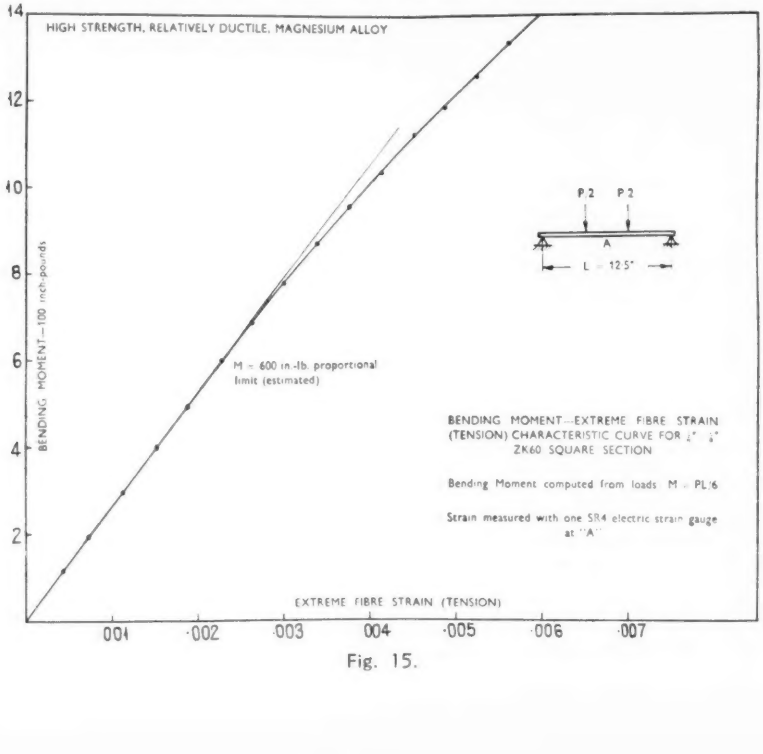

Fig. 15.

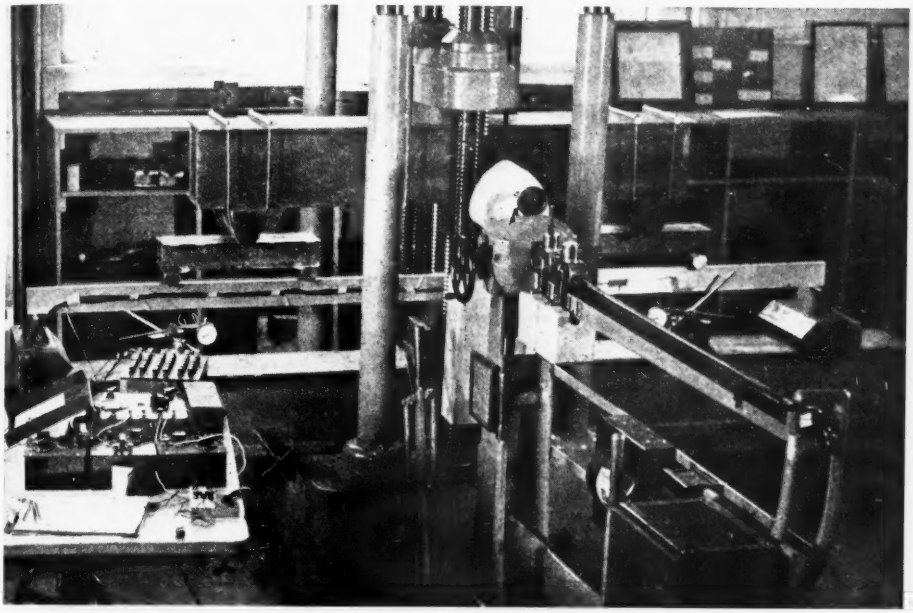

Plate I.
A 1 in. x 3 in. rectangular extrusion being tested as a beam on three supports. Span, L = 48 in.

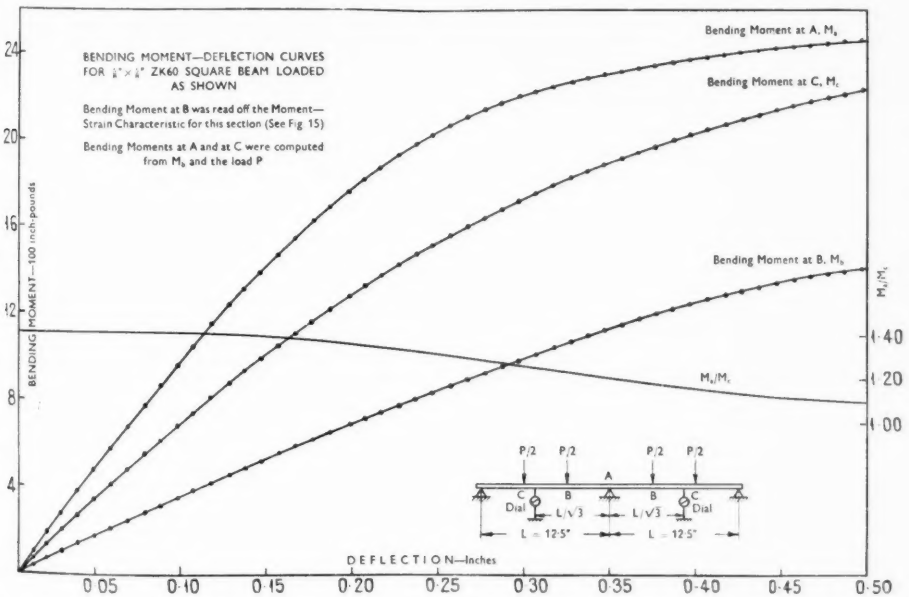

Fig. 16

beams, deflections at the two symmetrical points $L/\sqrt{3}$ distant from the middle support.

The following curves were plotted:— a load-deflection curve for the simple beam; a load-deflection curve for the redundant beam, the deflections used being the averages of the two dial readings; and a curve showing the variation of the ratio of the load carrying capacities of the two beams for the same deflection as this deflection increases. These curves are shown three to a sheet on Figs. 17, 18, 19, 20, 21, 22 and 23, respectively, for the seven alloys.

Interpretation of the results.

An examination of any one of Figs. 18, 19, 20, 21, 22 and 23 will reveal three points

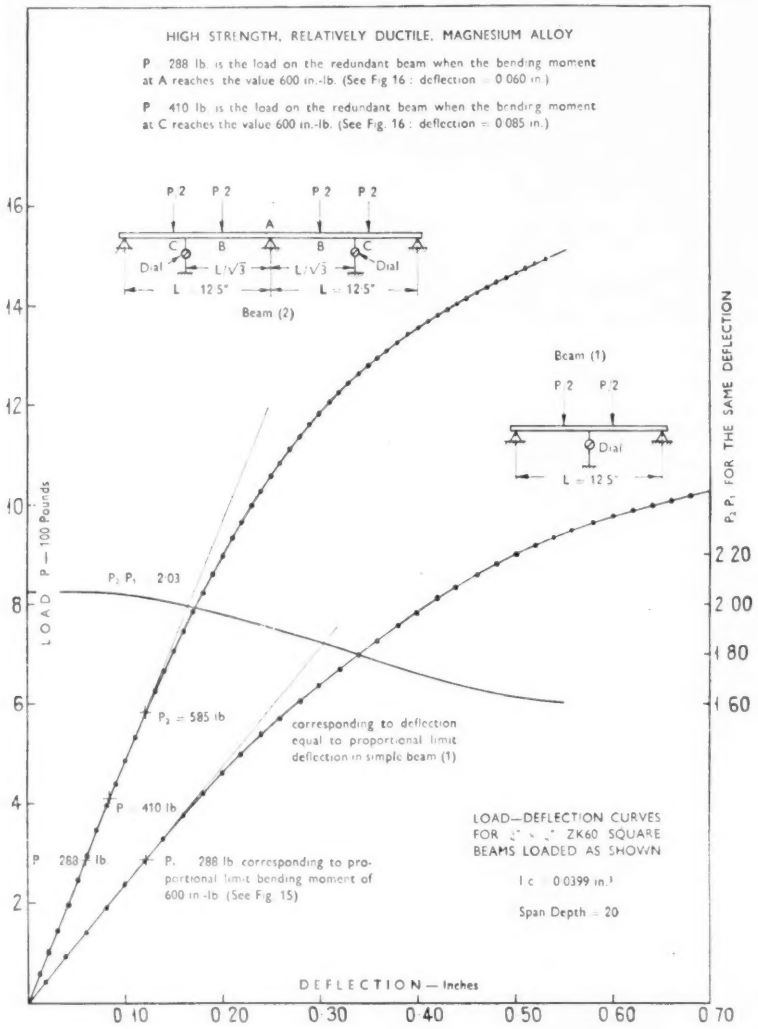
HIGH STRENGTH, RELATIVELY DUCTILE, MAGNESIUM ALLOY
P = 288 lb. is the load on the redundant beam when the bending moment at A reaches the value 600 in.-lb. (See Fig 16 : deflection = 0·060 in.)
P = 410 lb. is the load on the redundant beam when the bending moment at C reaches the value 600 in.-lb. (See Fig. 16 : deflection = 0·085 in.)
P/2 P/2 P/2 P/2
A
C B B C
Dial
L/√3 L/√3
L = 12·5" L = 12·5"
Beam (2)
Beam (1)
P/2 P/2
Dial
L = 12·5"
LOAD P — 100 Pounds
P₂/P₁ = 2·03
P₂ = 585 lb
P = 410 lb
P = 288 lb
P₁ = 288 lb corresponding to proportional limit bending moment of 600 in.-lb (See Fig 15)
corresponding to deflection equal to proportional limit deflection in simple beam (1)
P₂/P₁ FOR THE SAME DEFLECTION
LOAD—DEFLECTION CURVES FOR ½" × ½" ZK60 SQUARE BEAMS LOADED AS SHOWN
I c = 0·0399 in.⁴
Span Depth = 20
DEFLECTION — Inches
16
14
12
10
8
6
4
2
2·20
2·00
1·80
1·60
0·10
0·20
0·30
0·40
0·50
0·60
0·70

Fig. 17.

marked out, one on each of the three curves described above. The point on the simple beam curve corresponds to the load carried when the proportional limit in the centre section of the beam is first reached. This point was estimated from the curve in these six figures. In the case of the Dowmetal ZK60 extrusion (Fig. 17), which was run as part of Series A also, this proportional limit was estimated from the moment-strain characteristic curve (see discussion of Series A tests). The point on the redundant beam curve corresponds to a load which causes a deflection equal to the proportional limit deflection in the simple beam. The point on the P_2/P_1 curve shows the ratio of these two loads. This is in a sense a direct comparison of the load carrying capacities of

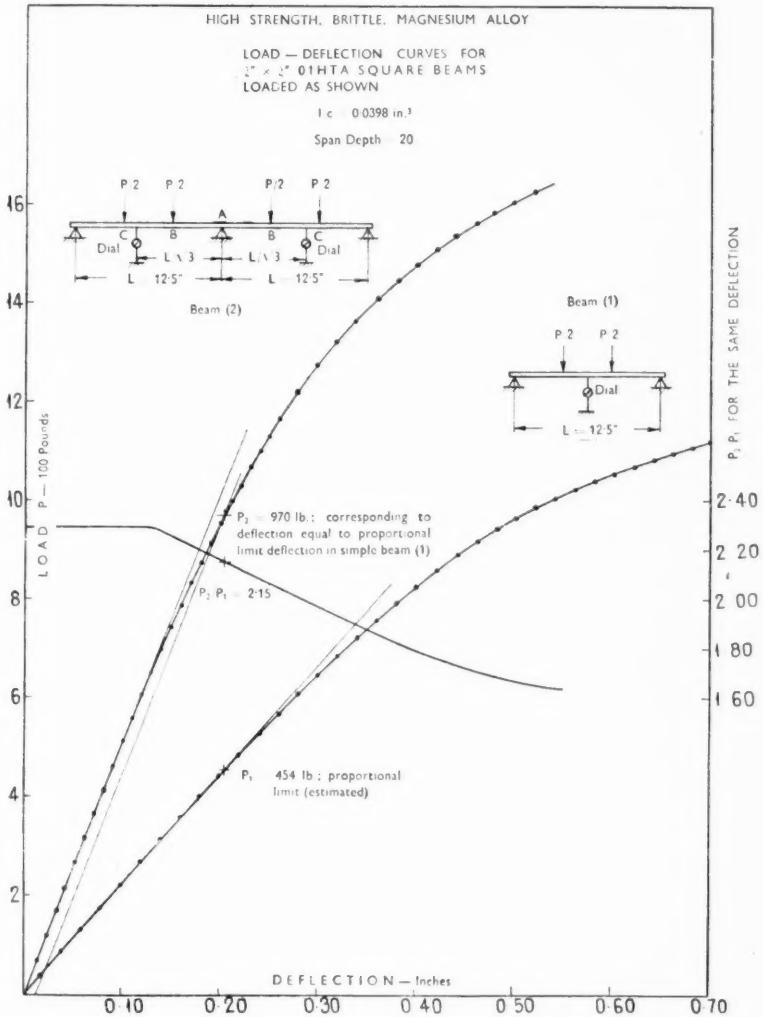
HIGH STRENGTH, BRITTLE, MAGNESIUM ALLOY
LOAD — DEFLECTION CURVES FOR
LOADED AS SHOWN
I c = 0·0398 in.⁴
Span Depth = 20
P/2 P/2 P/2 P/2
A
B B
C C
Dial Dial
L/3 L/3
L = 12·5" L = 12·5"
Beam (2)
Beam (1)
P/2 P/2
Dial
L = 12·5"
LOAD P — 100 Pounds
P₂ = 970 lb.: corresponding to deflection equal to proportional limit deflection in simple beam (1)
P₂/P₁ = 2·15
P₁ = 454 lb.: proportional limit (estimated)
P₂/P₁ FOR THE SAME DEFLECTION
DEFLECTION — Inches
0·10 0·20 0·30 0·40 0·50 0·60 0·70
2 4 6 8 10 12 14 16
1·60 1·80 2·00 2·20 2·40

Fig. 18.

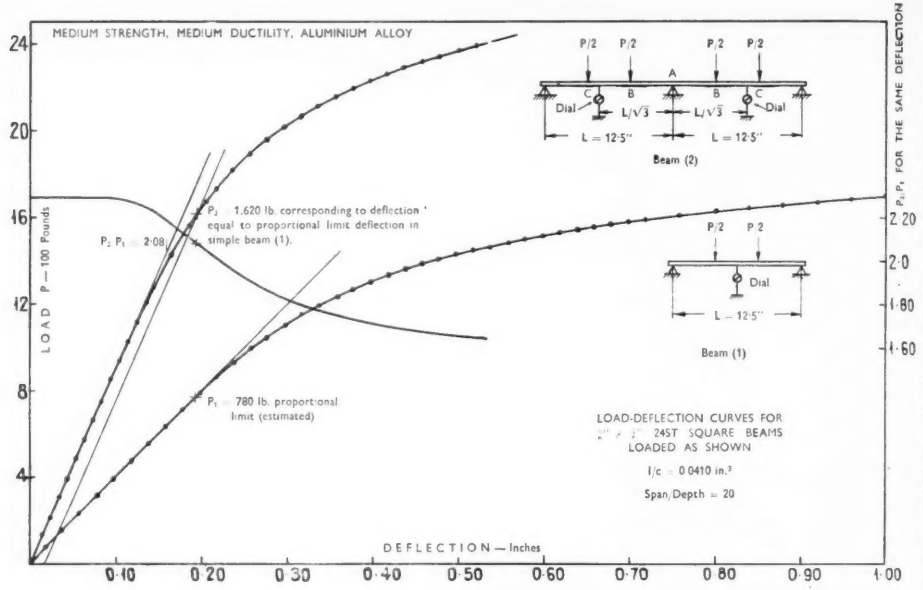
MEDIUM STRENGTH, MEDIUM DUCTILITY, ALUMINIUM ALLOY
LOAD P — 100 Pounds
DEFLECTION — Inches
P2/P1 FOR THE SAME DEFLECTION
P/2 P/2 P/2 P/2
A
B B
C C
Dial Dial
L/√3 L/√3
L = 12·5" L = 12·5"
Beam (2)
P2 = 1,620 lb. corresponding to deflection equal to proportional limit deflection in simple beam (1).
P2/P1 = 2·08
P/2 P/2
Dial
L = 12·5"
Beam (1)
P1 = 780 lb. proportional limit (estimated)
LOAD-DEFLECTION CURVES FOR
24ST SQUARE BEAMS
LOADED AS SHOWN
I/c = 0·0410 in.3
Span/Depth = 20

Fig. 19.

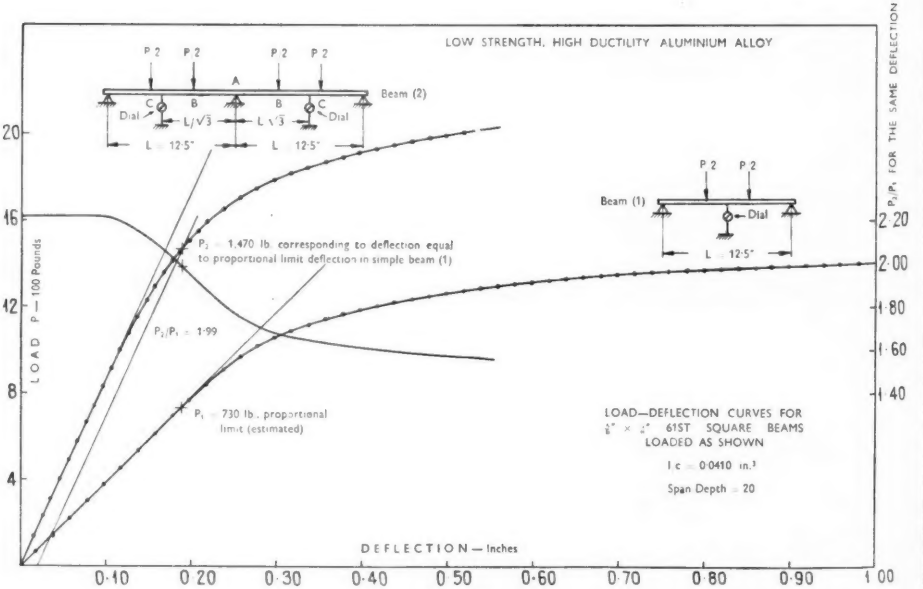
LOW STRENGTH, HIGH DUCTILITY ALUMINIUM ALLOY
LOAD P — 100 Pounds
DEFLECTION — Inches
P2/P1 FOR THE SAME DEFLECTION
P/2 P/2 P/2 P/2
A
B B
C C
Dial Dial
L/√3 L/√3
L = 12·5" L = 12·5"
Beam (2)
P2 = 1,470 lb. corresponding to deflection equal to proportional limit deflection in simple beam (1)
P2/P1 = 1·99
P/2 P/2
Beam (1)
Dial
L = 12·5"
P1 = 730 lb. proportional limit (estimated)
LOAD—DEFLECTION CURVES FOR
61ST SQUARE BEAMS
LOADED AS SHOWN
I c = 0·0410 in.3
Span Depth = 20

Fig. 20

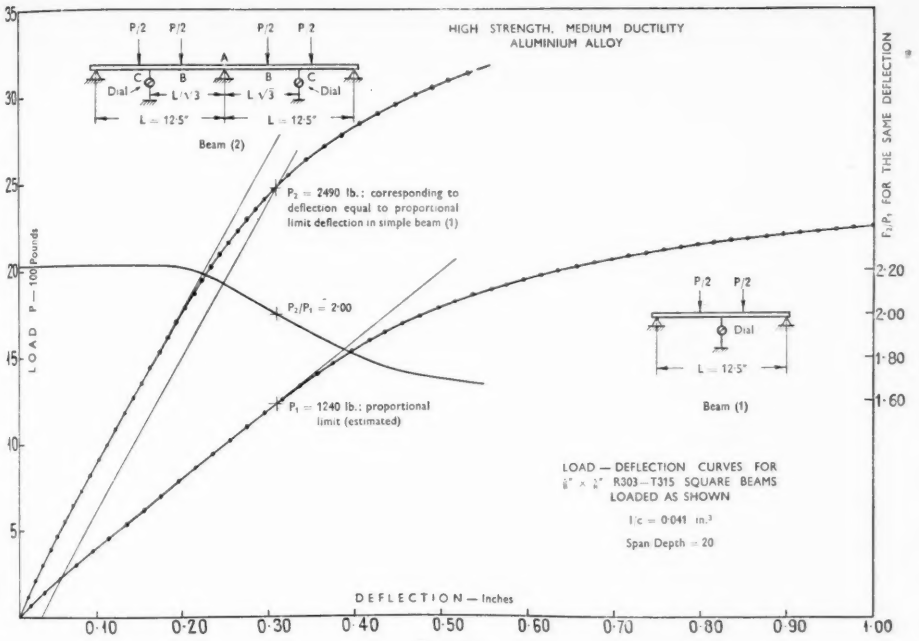
HIGH STRENGTH, MEDIUM DUCTILITY ALUMINIUM ALLOY
P/2 P/2 P/2 P/2
A
B B
C C
Dial Dial
L/√3 L/√3
L = 12·5" L = 12·5"
Beam (2)
P₂ = 2490 lb.: corresponding to deflection equal to proportional limit deflection in simple beam (1)
P₂/P₁ = 2·00
P₁ = 1240 lb.: proportional limit (estimated)
P/2 P/2
Dial
L = 12·5"
Beam (1)
LOAD — DEFLECTION CURVES FOR ⅛" × ½" R303—T315 SQUARE BEAMS LOADED AS SHOWN
I/c = 0·041 in.³
Span Depth = 20
LOAD P — 100 Pounds
P₂/P₁, FOR THE SAME DEFLECTION
DEFLECTION — Inches
0·10 0·20 0·30 0·40 0·50 0·60 0·70 0·80 0·90 1·00
5 10 15 20 25 30 35
1·60 1·80 2·00 2·20

Fig. 21.

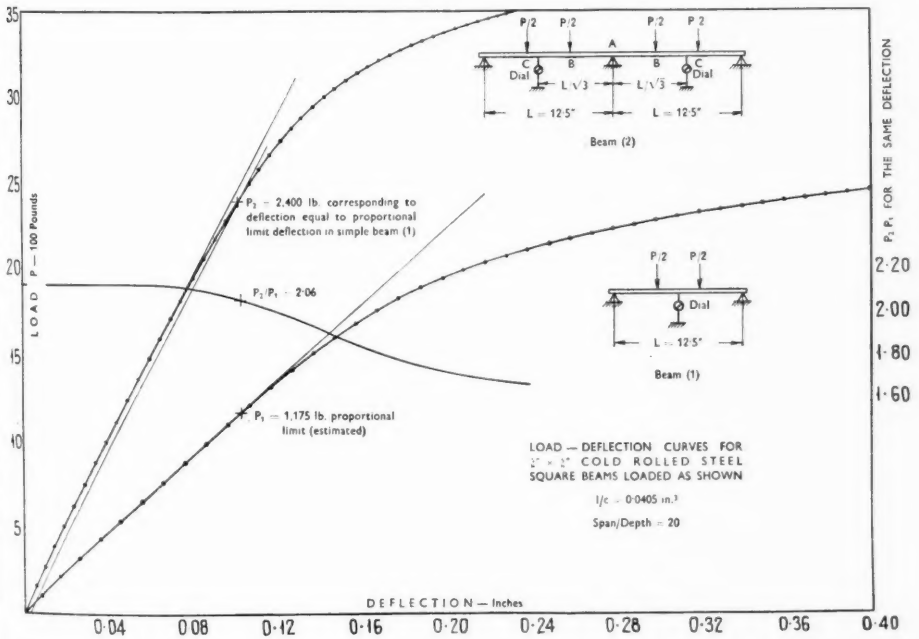
P/2 P/2 P/2 P/2
A
B B
C C
Dial Dial
L/√3 L/√3
L = 12·5" L = 12·5"
Beam (2)
P₂ = 2,400 lb. corresponding to deflection equal to proportional limit deflection in simple beam (1)
P₂/P₁ = 2·06
P₁ = 1,175 lb. proportional limit (estimated)
P/2 P/2
Dial
L = 12·5"
Beam (1)
LOAD — DEFLECTION CURVES FOR ⅛" × ½" COLD ROLLED STEEL SQUARE BEAMS LOADED AS SHOWN
I/c = 0·0405 in.³
Span/Depth = 20
LOAD P — 100 Pounds
P₂/P₁, FOR THE SAME DEFLECTION
DEFLECTION — Inches
0·04 0·08 0·12 0·16 0·20 0·24 0·28 0·32 0·36 0·40
5 10 15 20 25 30 35
1·60 1·80 2·00 2·20

Fig. 22.

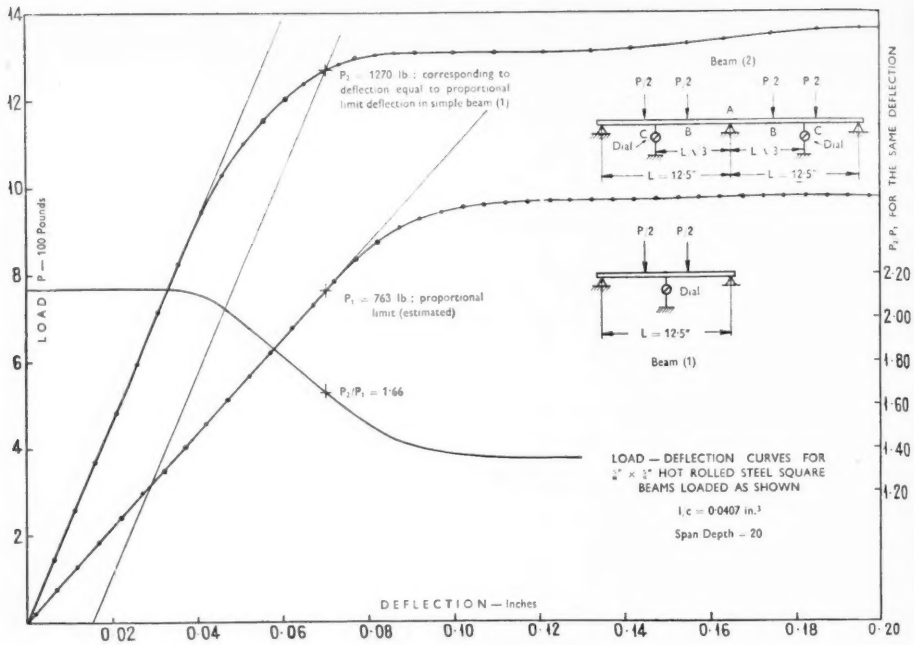
LOAD P — 100 Pounds
DEFLECTION — Inches
P₂ = 1270 lb.: corresponding to deflection equal to proportional limit deflection in simple beam (1)
P₁ = 763 lb.: proportional limit (estimated)
P₂/P₁ = 1·66
Beam (2)
Beam (1)
Dial
L = 12·5"
LOAD — DEFLECTION CURVES FOR ½" × ½" HOT ROLLED STEEL SQUARE BEAMS LOADED AS SHOWN
I.c = 0·0407 in.⁴
Span Depth = 20
P₂, P₁ FOR THE SAME DEFLECTION

Fig. 23.

the two systems for the same maximum deformations. The following conclusions may be drawn from these curves.

First: If the load carrying capacity of the redundant beam is based on the elastic or proportional limit stress, its strength is the same as that of the simple beam. This means that the potentiality of the redundant system is exploited only to a pitifully small extent. On the other hand, if the load carrying capacity of this redundant beam is based on a maximum deflection equal to the proportional limit deflection of the simple beam (the yardstick), it is evident from the curves that even under such loads the resulting deformations in the redundant systems are still of the order of magnitude of elastic deformations, that is, the deviation from the original straight line is still very small. In no case is this deviation more than 0.03 in. (Fig. 21, for R303-T315), or $3/12.5 = 0.24$ per cent. of the span. The ratio of this load to that based on the proportional or elastic limit stress ranges from approximately 1.66 for the hot rolled steel (Fig. 23) to approximately 2.15 for the Dowmetal magnesium alloy 01HTA (Fig. 18). Hence, the elastic or proportional limit stress is a poor criterion of strength in redundant structures, especially so in such structures made of the alloys of magnesium and of aluminium.

Second: The presence in hot rolled steel of a definite yield point leads to a definite condition of yield in the structure, be it simple or redundant. Fig. 23 shows this clearly for beams. The limit load for the simple beam is approximately 970 lb., while that for the redundant beam is definitely 1,310 lb. Thus the redundant system may be said to be 35 per cent. stronger than the simple system, and there cannot possibly be any ambiguity in such a statement, these two conditions being well defined. The P_2/P_1 curve becomes horizontal at 1.35. (Analytically this ratio

is 1.33.) In contrast with this none of the light metals, including the cold rolled steel, has such a definite yield condition.

In order to compare the capacities of the two systems, simple and redundant, what better yardstick is there than the proportional limit deflection in the simple beam? Therefore, the load P_2 in the redundant system, corresponding to this proportional limit deflection in the simple beam, is compared with P_1 in the simple system which causes this deflection. This ratio averages around 2 for the five light metals and the cold rolled steel. It is only 1.66 for the hot rolled steel.

These values are only approximate, inasmuch as no attempt was made to correct for the lack of rigidity of the testing machine when the deflections were plotted. But such a correction would only tend to increase the steepness of the redundant beam curves, thus showing to still better advantage the superiority of the light metals, *i.e.*, the value of P_2 for the same deflection would be much higher. Such details were dispensed with on the grounds that they would distract attention from the main issues of this dissertation. Thus the statement that the load carrying capacity of redundant beams made of the light metals is relatively higher, because of the continuing ability of the beam sections to contribute increasing resisting moments, is completely proven.

DESIGN OF BEAMS.

From the foregoing discussion and experiments it is implied that the simplified procedure in designing steel structures, more specifically the rule offered as a guide in the application of Limit Design for the design of continuous steel beams, may be applied to light metal construction without any modification other than that some value of the stress be decided upon—low enough so as to avoid excessive deformations but high enough so as to make use of the material as efficiently as possible—to take the place of the yield point stress in structural steel. It is proposed here to use for the stress criterion the yield strength at 0.2 per cent. offset in tension, in tension for no reason other than that this is a comparatively easier test than compression, and 0.2 per cent. offset because this is the most commonly mentioned deviation in specifications and guaranteed minimum properties.

The assumption of equalisation of moments is not quite justified as in the case of steel in which moments can, within limits, actually equalise; and certainly one may not always assume equalised moments for *all* load combinations. But for the sake of illustration this assumption is made here. The limitations of such a procedure will be discussed under Evaluation of the Theory of Limit Design.

In making an assumption of the bending moment which a section may offer in resistance to loading, there are four methods available to guide the designer. The first and most logical, is by direct experiment. That is, the load-deflection curve of some simple beam (which could easily be standardised) could be obtained, and some value of the bending moment could be decided upon as a useful property of that particular section. Such a bending moment, for example, could be that corresponding to the load when the deviation from the original straight line in the load-deflection curve is a certain percentage of the span, say 0.2 per cent.

The second method is based on the assumption of an equalised distribution of stresses from one side of the beam to the neutral axis and an identical distribution of stresses of opposite sign on the other side—the so-called rectangular distribution of stresses.[13], [14] This assumption can be practically satisfied only in the case of structural steel, and the more closely the stress-strain curve of the material approaches that of steel the greater the justification in using this method.

The third method is one proposed by F. P. Cozzone[15] and further elaborated on by the engineering department of the Curtiss-Wright

Corporation.[16] It consists in an assumed trapezoidal distribution of stresses (an approximation of the characteristic shape of the stress-strain curves of the light metals), based on an implied arbitrarily chosen value of maximum stress. The method is simple only for rectangular sections; it becomes tedious when applied to other sections, such as I-sections.

The fourth method is based on the assumption that the usual Applied Elasticity formula, $M = sI/c$, applies past the elastic limit, thereby utilising the fictitious stress as something analogous to the so-called modulus of rupture, only in this case there is no rupture involved. This last method is clearly the most practical inasmuch as the usual handbooks prepared by the different manufacturers already contain the necessary I/c values.

It is proposed here to use this last method in making the assumption for the resisting moment that may be assigned to a beam section. Having made this assumption the design follows the same procedure as in the case of steel beams. The following experiments were designed to determine more or less how much margin of safety such a procedure leaves in both the redundant and the simple beams, and to point out the possible lines of attack in a research programme that could very well be undertaken by the large manufacturing concerns.

EXPERIMENTS: SERIES C (Figs. 24 to 30).

This series of experiments, like the first two series, involves the test of a simple beam (the yardstick) and of a redundant beam. For the sake of convenience, the load combination was made to be much simpler than in the preceding experiments. The two beams and the corresponding bending moment diagrams (in the elastic range for the redundant beam) are shown in Figs. (f) and (g).

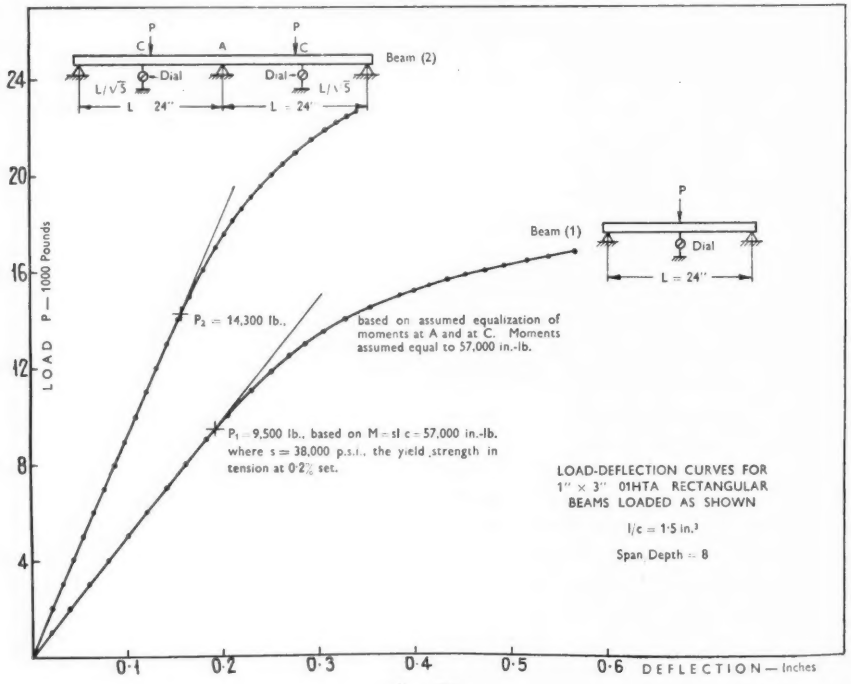

Fig. 24.

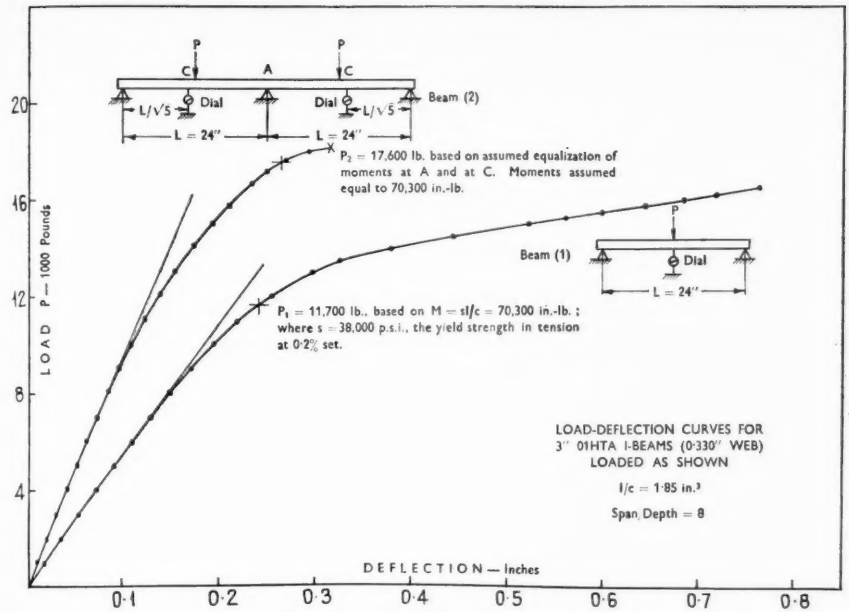
P
C
A
P
C
L/√5
Dial
Dial
L/√5
Beam (2)
L = 24"
L = 24"
P₂ = 17,600 lb. based on assumed equalization of moments at A and at C. Moments assumed equal to 70,300 in.-lb.
Beam (1)
Dial
L = 24"
P₁ = 11,700 lb., based on M = sI/c = 70,300 in.-lb. ; where s = 38,000 p.s.i., the yield strength in tension at 0·2% set.
LOAD-DEFLECTION CURVES FOR 3" 01HTA I-BEAMS (0·330" WEB) LOADED AS SHOWN
I/c = 1·85 in.³
Span/Depth = 8
LOAD P — 1000 Pounds
DEFLECTION — Inches
20
16
12
8
4
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8

Fig. 25.

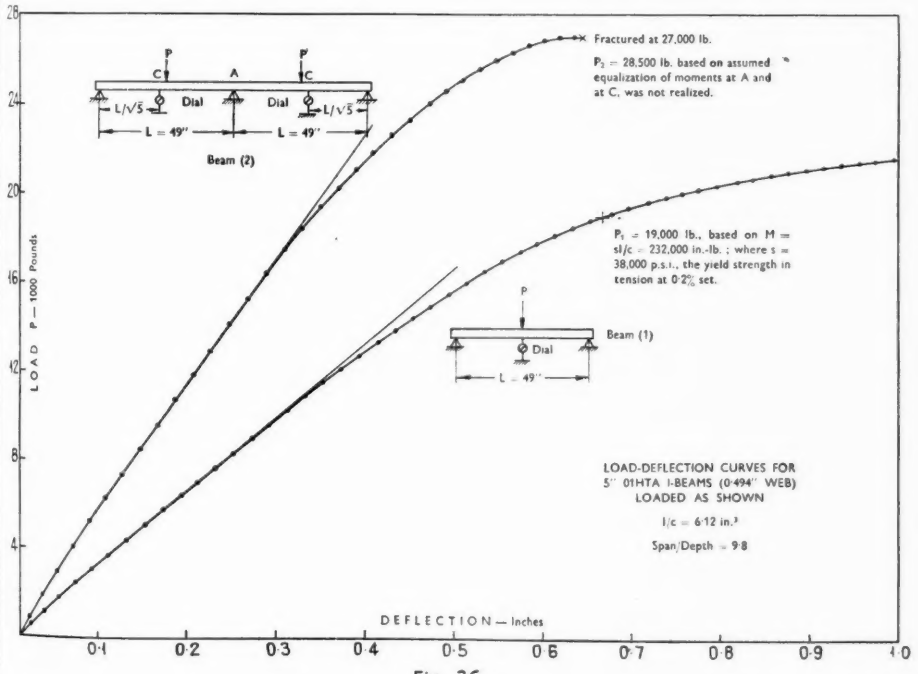
P
C
A
P
C
L/√5
Dial
Dial
L/√5
L = 49"
L = 49"
Beam (2)
Fractured at 27,000 lb.
P₂ = 28,500 lb. based on assumed equalization of moments at A and at C, was not realized.
P₁ = 19,000 lb., based on M = sI/c = 232,000 in.-lb. ; where s = 38,000 p.s.i., the yield strength in tension at 0·2% set.
P
Beam (1)
Dial
L = 49"
LOAD-DEFLECTION CURVES FOR 5" 01HTA I-BEAMS (0·494" WEB) LOADED AS SHOWN
I/c = 6·12 in.³
Span/Depth = 9·8
LOAD P — 1000 Pounds
DEFLECTION — Inches
28
24
20
16
12
8
4
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1·0

Fig. 26.

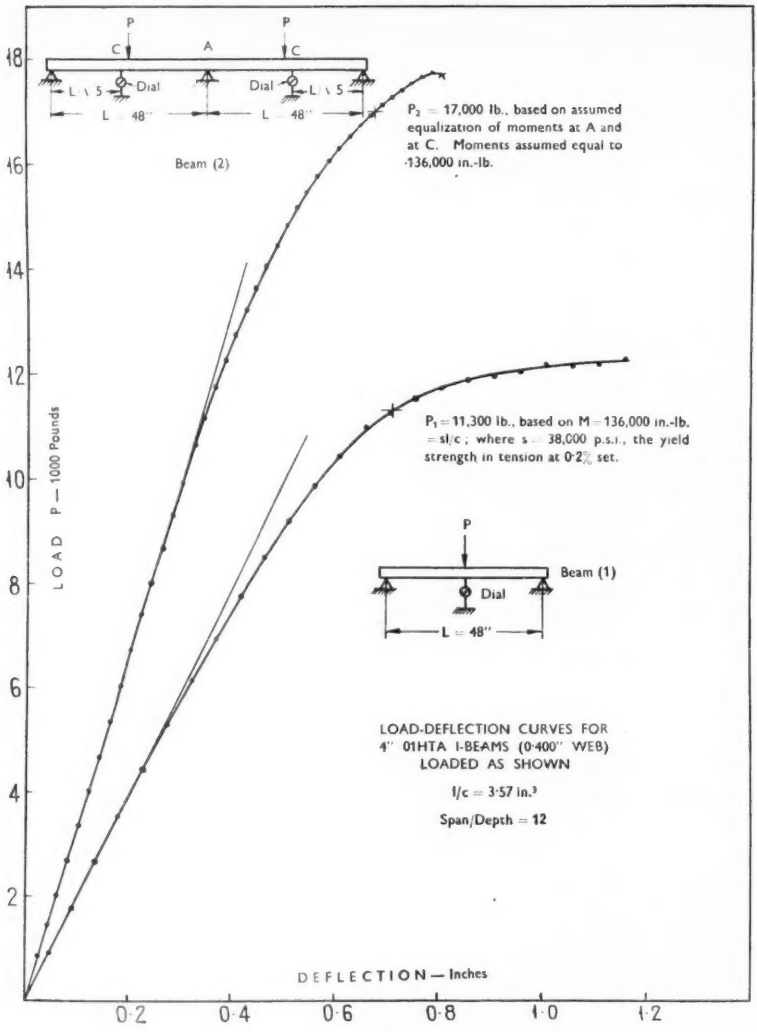

Fig. 27.

The accompanying table shows the extrusions tested, the spans of the beams, and the span-to-depth ratios.

Test No.	Section.	Alloy	Span, L	Span/Depth
1	1″ × 3″ rectangle	01HTA magnesium	24″	8
2	3″ I (0.330″ web)	01HTA ,,	24	8
3	5″ I (0.494″ web)	01HTA ,,	49	9.8
4	4″ I (0.400″ web)	01HTA ,,	48	12
5	3″ I (0.330″ web)	01HTA ,,	48	16
6	1″ × 3″ rectangle	61ST aluminium	48	16
7	3″ I (0.153″ web)	61ST ,,	48	16

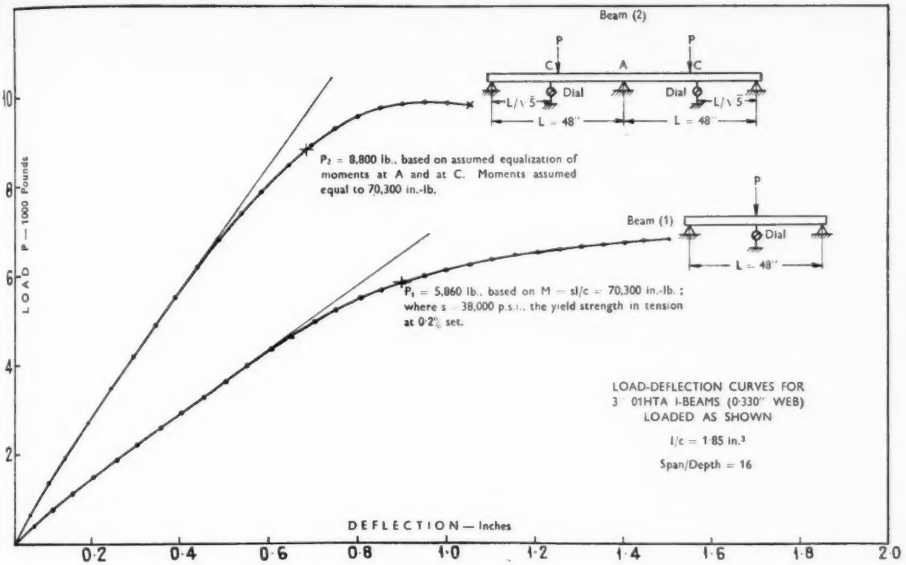
Beam (2)
P
C
A
C
Dial
Dial
L/√5
L/√5
L = 48"
L = 48"
P₂ = 8,800 lb., based on assumed equalization of moments at A and at C. Moments assumed equal to 70,300 in.-lb.
Beam (1)
P
Dial
L = 48"
P₁ = 5,860 lb., based on M = sI/c = 70,300 in.-lb.; where s = 38,000 p.s.i., the yield strength in tension at 0·2% set.
LOAD-DEFLECTION CURVES FOR 3" 01HTA I-BEAMS (0·330" WEB) LOADED AS SHOWN
I/c = 1·85 in.³
Span/Depth = 16
LOAD P — 1000 Pounds
DEFLECTION — Inches
0·2
0·4
0·6
0·8
1·0
1·2
1·4
1·6
1·8
2·0
2
4
6
8
10

Fig. 28.

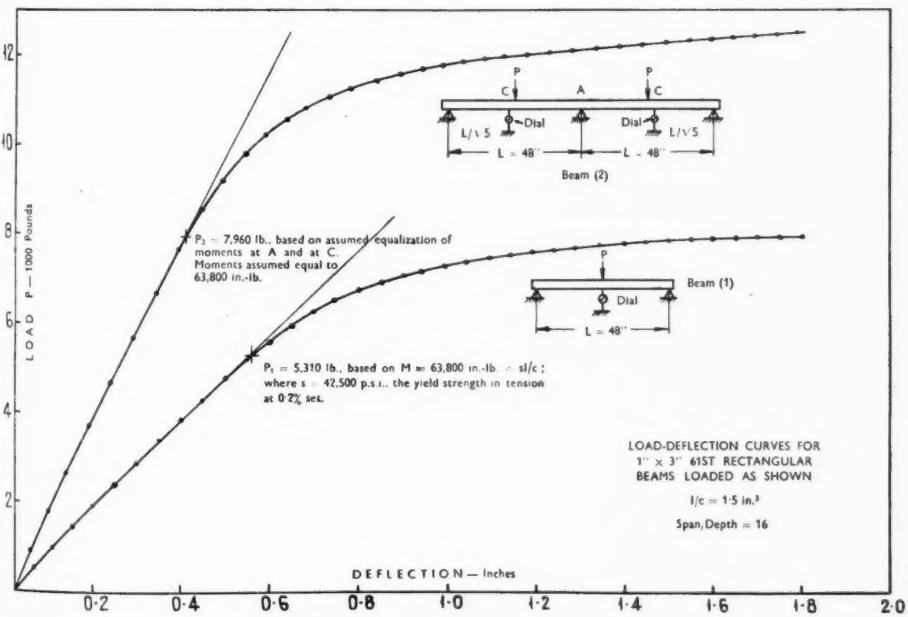
P
C
A
C
Dial
Dial
L/√5
L/√5
L = 48"
L = 48"
Beam (2)
P₂ = 7,960 lb., based on assumed equalization of moments at A and at C. Moments assumed equal to 63,800 in.-lb.
P
Beam (1)
Dial
L = 48"
P₁ = 5,310 lb., based on M = 63,800 in.-lb. = sI/c; where s = 42,500 p.s.i., the yield strength in tension at 0·2% set.
LOAD-DEFLECTION CURVES FOR 1" × 3" 61ST RECTANGULAR BEAMS LOADED AS SHOWN
I/c = 1·5 in.³
Span/Depth = 16
LOAD P — 1000 Pounds
DEFLECTION — Inches
0·2
0·4
0·6
0·8
1·0
1·2
1·4
1·6
1·8
2·0
2
4
6
8
10
12

Fig. 29.

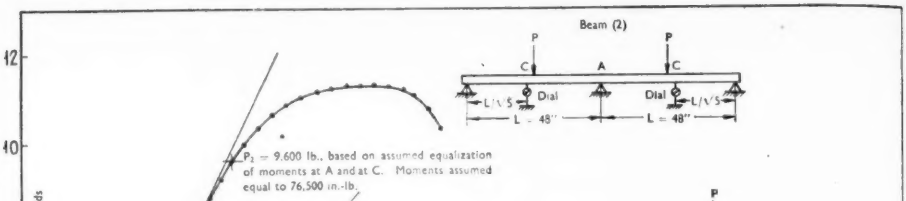

Fig. 30.

The beams with 24-inch spans were run in the Amsler hydraulic machine. All the rest were run in the 200,000 lb. Rhiele machine with the exception of the 1 in. × 3 in. 61ST rectangular simple beam, which was run in a 10,000 lb. Tinius Olsen hand-bending machine. All deflections were measured with Federal dial gauges. The deflections in the redundant beams were taken at two symmetrical points whose distance from the outer supports was $L/\sqrt{5}$. These are the points of maximum deflection in the elastic range. No correction was made for the shift of these points after the passing of the elastic limit, nor for the lack of rigidity of the testing machine.

The following readings were taken:— the load P_1 for the simple beam, the deflection

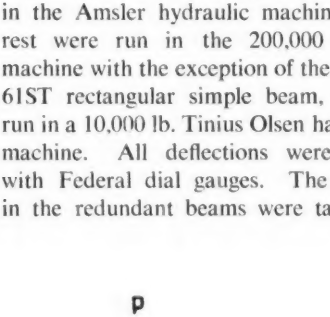

Fig. f.

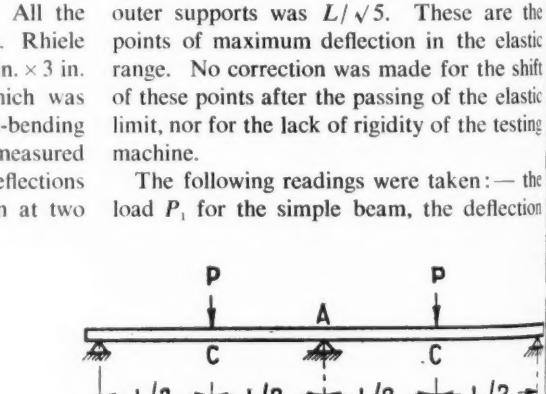

Fig. g.

at the centre; the total load $2P_2$ for the redundant beam, and the deflection at the above-mentioned points.

The following two curves were plotted:—a load-deflection curve for the simple beam, and a load-deflection curve for the redundant beam, the deflections plotted being the averages of the readings of the dial gauges. These curves are presented in Figs. 24 to 30 in the order of listing in the above table.

INTERPRETATION OF THE RESULTS.

In tests 1, 4, 5, 6 and 7 it is seen from the curves (Figs. 24, 27, 28, 29 and 30, respectively) that the loads P_2 on the redundant beams, which were based on the assumed equalisation of bending moments at sections A and C (Fig. (g)), produced deflections no greater than those in the simple beams under the loads P_1 based on the moment $M=sI/c$, where for s the yield strengths at 0.2 per cent. offset in tension were used. (See the stress-strain curves given in Figs. 2 and 4.) In test 2 the resulting deformation of the redundant system (Fig. 25) was greater than the corresponding deformation in the simple system, while in test 3 (Fig. 26) the expected value of the load based on equalisation of moments was not realised. This beam failed laterally and fractured locally under one of the loading blocks—no doubt because of a shortcoming in the test set-up.

For the particular loading used the conclusion may be drawn that, in the interests of safety, the method of assumed equalisation of moments should not be used for span-to-depth ratios less than 12 for the standard I-extrusions of Dowmetal 01HTA magnesium alloy. This raises the question of the safety factor.

The underlying philosophy of Limit Design, which is concerned with the determination of true or arbitrarily chosen limiting conditions for a structure, implies that the factor of safety should be applied not on the elastic limit stress to obtain a working stress, but rather on the limiting loads, thereby obtaining working loads. In design this indicates that the safety factor should take the form of an overload factor by which the given loads (determining which, incidentally, is itself also a vital aspect of design) are multiplied to obtain maximum loads. The structure should then be so designed that under these maximum loads it be brought as close to the limiting conditions as possible.

Returning to the tests under discussion, if a safety factor of, say, 2 is used, it is seen that in all seven systems, simple as well as redundant, the loads are well within the proportional limit. Thus it may be expected that under such loads these systems will function without any permanent deformations. Further examination of Figs. 25, 26, 27 and 28, all for Dowmetal 01HTA magnesium alloy I-sections, will reveal a little cross at the end of each redundant beam curve. This cross indicates fracture, invariably local fracture caused by concentrated pressure from a loading block or from the middle support. No such fracture occurred in any of the aluminium alloy sections. Hence, it should also be stated here that, in the case of 01HTA magnesium alloy extrusions, probably much larger safety factors should be applied in view of the comparative brittleness of this particular alloy. This will be discussed further.

EXPERIMENT: SERIES D (Fig. 31).

This last experiment was prompted by the startling discovery that the existing I-sections in aluminium and magnesium handbooks are practically identical copies of the sections which the steel industry has gradually developed and found acceptable. The differences, which are extremely minor, are changes in the fillet radii. This much change has been recognised as necessary by the designers. It makes one wonder whether any thought has ever been paid to the fact that failures of members with thin sections invariably follow from local buckling, or crippling, in compression of these sections. Whether

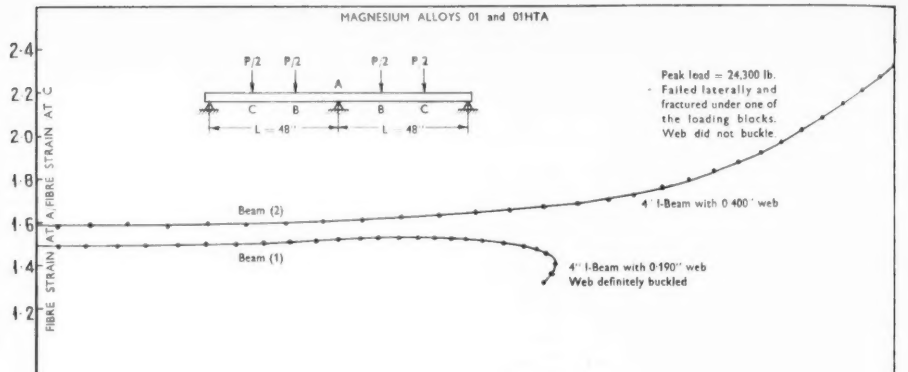
MAGNESIUM ALLOYS 01 and 01HTA
FIBRE STRAIN AT A / FIBRE STRAIN AT C
2·4
2·2
2·0
1·8
1·6
1·4
1·2
P/2 P/2 P/2 P/2
A
C B B C
L = 48" L = 48"
Peak load = 24,300 lb.
Failed laterally and fractured under one of the loading blocks.
Web did not buckle.
Beam (2)
4" I-Beam with 0·400" web
Beam (1)
4" I-Beam with 0·190" web
Web definitely buckled
RATIO OF EXTREME FIBRE STRAIN AT "A" TO THAT AT "C" PLOTTED AGAINST LOAD P FOR A BEAM ON THREE SUPPORTS LOADED AS SHOWN
Beam (1) Dowmetal 01 Alloy: 4" I-Section, 0·190" web, 1·73 lb./ft.; I/c = 3·03 in.³
Beam (2) Dowmetal 01HTA Alloy: 4" I-Section, 0·400" web, 2·37 lb./ft.; I/c = 3·59 in.³
LOAD P — 1000 Pounds
2 4 6 8 10 12 14 16 18 20

Fig. 31.

such local buckling is elastic or inelastic, it is well known that the modulus of elasticity, or some modification of it, enters into the picture. Therefore, it is imperative that provision be made for the lower moduli of the light metals, in that the thinnest sections should accordingly be made heavier than they are in steel.

Two 4 in. I-sections with different web thicknesses were tested as identical beams on three supports. The set-up was similar to that used in Series A and Series B (Figs. (e) and 31). One beam was of Dowmetal 01 magnesium alloy with a 0.190 in. web. The other was of Dowmetal 01HTA magnesium alloy with a 0.400 in. web. Three SR4 strain gauges were installed on the tension side of the beam at sections A and C.

Readings for the total load $2P$ and for the strains at the three sections were taken, and the following curve was plotted for each beam:— the variation with the load P of the ratio of the extreme fibre strain at A to that at C, using for the strain at section C the mean of the strain readings at the two symmetrically located sections C. These two curves are shown in Fig. 31.

Strictly speaking, it is not correct to compare the two alloys since the yield strengths at 0.2 per cent. offset in compression are different. An unpublished report of the Dow Chemical Company, compiled in September 1943, gives values for this stress of 23,000 p.s.i. for the 01 alloy and 36,000 p.s.i. for the 01HTA alloy (not guaranteed minimum properties). The tension yield strengths are about the same. Notwithstanding this difference, the ratio of the two yield strengths in compression is so much smaller than the ratio of the two web thicknesses that it is still possible to compare the two beams, at least qualitatively.

From Fig. 31 it can be seen that, under a load of about 8,500 lb., beam (1) with the thin web began to develop local failure. The web began to buckle in section A where the bending moment and the shear were highest. This is evident from the fact that the curve starts to fall. The ratio of the strain at A to that at C is an index of beam behaviour.

That is, for pure beam action, as for example in a solid rectangular section, the strain at A should continually grow at an increasing rate, so that the ratio of this strain to the strain at section C would continually increase also. In beam (2) with the heavy web this is substantially what happened—the curve keeps rising. In beam (1) the strain at A reached a peak under a load of approximately 12,000 lb., which was also the peak load. Under this load the web over the centre support was definitely kinked, and this remained even after unloading. On the other hand, beam (2) developed a peak load of 24,300 lb. without buckling of the web. It failed laterally and fractured locally at one flange under a loading block—again a flaw in the test set-up.

The difference between the two performances was so marked as to justify the conclusion that the section with the heavier web is the more efficient one, *e.g.*, from the standpoint of the strength-to-weight ratio: $24{,}300/2.37 = 10{,}200$, while $12{,}000/1.73 = 6{,}920$ only. [See Fig. 31. 2.37 is the weight in pounds per foot of beam (2), while 1.73 is that of beam (1).]

No comparable aluminium alloy sections were available for a similar test.

In all fairness, attention should be directed to the fact that only two out of an infinite number of load combinations were tested in these experiments, and only a few extrusions and a small number of span-to-depth ratios were used. It is obvious that to do justice to this subject would require much more time than has been available, much better testing facilities, and a more ready access to all commercially available forms of these extrusions. As mentioned earlier, such research could, and should, be undertaken by the manufacturing concerns, and they should present in table form information similar to that contained in the standard steel handbooks, information which gives, for example, such vital data as which of the two criteria controls in the design and in what circumstances —the deflections or the average shearing stresses in the webs of thin sections.

EVALUATION OF THE THEORY OF LIMIT DESIGN—CONCLUSIONS AND RECOMMENDATIONS.

The methods of Applied Elasticity make use of the elastic limit stress as the one and final criterion of strength. After all the necessary equations have been solved and all the arithmetical gymnastics performed, there still remains that one final stipulation: at no one point in a structure, regardless of whether that structure is simple or redundant, must the elastic limit stress be exceeded; and, to make certain that this shall be achieved, a factor is applied to the elastic limit stress to obtain the so-called working stress. This method is unsatisfactory for three important reasons.

First, this factor, often called a safety factor, is in reality a factor of ignorance.[17] It is intended to take care of the many unaccountable factors that enter into the actual construction and service after the plans leave the designer. The factor as such should be applied to the maximum loads to obtain working loads.

Second, the method conveniently ignores secondary stresses which are difficult to compute, as well as stresses around rivet holes in the connections, around points of application of loads and reactions, around junction points of web and flange in I-sections. Thus there is involved some sort of a double standard. There are cases in which the elastic limit stress must control, and other cases in which, frankly, it does not have to control. Even if these secondary items are ignored and only pure beam action is considered, the elastic limit stress is still an inadequate criterion of the strength of redundant structures, especially those built of the light metals, as has already been demonstrated. Because all modern construction is based on continuity, some other criterion should be adopted. The maximum elastic deformations of strictly comparable non-redundant systems is proposed as a suitable yardstick for allowable deformations of redundant systems.

Third, the assumptions made in the use of the Applied Elasticity equations are seldom satisfied in practice. The alignment of points of support is never perfect. Members which are assumed to be perfectly straight rarely satisfy this condition. They are usually sprung into place. If the middle support of a beam resting on three supports were just a tiny fraction of the span higher than the other two supports, the elastic limit stress at the centre would be reached long before the loads would attain even the values based on elastic behaviour. Such misalignments cannot be controlled from the designer's desk. The best that can be done is to impose certain tolerances in shop or field construction. This means that the significance of elaborate arithmetical computations is all but lost, and that the time spent on them is all but wasted. If only approximate values can be obtained, it would be better and more logical in the circumstances to apply Kist's principle to design.

As has been stated earlier, the fact has to be faced that the very nature of the stress-strain characteristics of the light metals precludes any exact determination of limiting values. Therefore, whatever method is used when the elastic limit is passed can only be an approximate method. Applied to structures made of these metals, Limit Design takes its place among other approximate methods. The only virtue it may claim is its underlying philosophy of according primary importance to primary considerations and secondary importance to secondary considerations. While Applied Elasticity is concerned with, among other things, the determination of the instantaneous stress distribution, Limit Design ignores it completely. Once the limiting conditions have been decided upon and the structure has been designed on the basis of these conditions, then whatever is the stress distribution for loads below the limit loads is of no consequence. It is only of academic interest. Its determination does not contribute to the theory of strength. In certain cases it might be of interest to know how the various elements behave in all the stages leading to the limiting conditions, but such knowledge would be of more value to analysis than to design.

Admittedly, both Applied Elasticity and Limit Design are, in the words of Professor Kist, "only caricatures of reality,"[6] but the basic concept of Limit Design is more faithful to reality. How close its assumptions can be realised in the over-loaded limit conditions depends on the ductility of the material of which the component parts of the structure are made and also, upon the efficiency of the connections.

Ductility is a property of metals for which, unfortunately, neither industry nor the profession has as yet devised an absolute measure. Yet ductility is at least as important as strength for structural purposes. Professor George Welter of the Ecole Polytechnique, in his as yet unpublished discussion of Professor Van den Broek's paper, "Evaluation of Airplane Metals,"[18] hit the nail on the head when he said, "Only two indirect indices, the elongation and the reduction in area, are nearly all we possess on which to estimate this basic characteristic. We do not even know the exact meaning of these values in relation to ductility." He also says, "Non-symmetrical loading, insufficient alignment of the elements, are in general the external sources of uncontrollable, localised working stresses. Without any doubt, ductility is the most effective insurance against high stress concentration factors."

To illustrate what Professor Welter means, attention is invited to the data contained in Figs. 2 and 6, the stress-strain curves of Dowmetal magnesium alloy ZK60 and of cold rolled steel, respectively. The ZK60 specimen manifested a 28 per cent. elongation in two inches and a 48 per cent. reduction in area. The cold rolled steel specimen elongated only 18 per cent. and reduced its area by the slightly greater amount of 57 per cent. And yet when $\frac{5}{8}$ in. square bars of the two alloys were bent in the bending machine

over the same radius of $\frac{1}{4}$ in., the cold rolled steel bar showed separation cracks only at, or near, 180 degrees, while the ZK60 bar fractured along a 45-degree line at approximately 45 degrees of bend. (See Plate II.) It is recommended that the bend test be standardised as a measure of ductility.

Until absolute standards and measures are set for this property of metals, ductility, the limitations of Limit Design can be described only in the most general terms. If, as seems to be the case, the bend test is a better index of ductility than elongation and reduction in area, then much caution should be exercised in applying the simplified methods of Limit Design to the two alloys of Dowmetal that were tested, particularly 01HTA. The new experimental alloy, ZK60, does not shatter the way 01HTA does, and it has brilliant

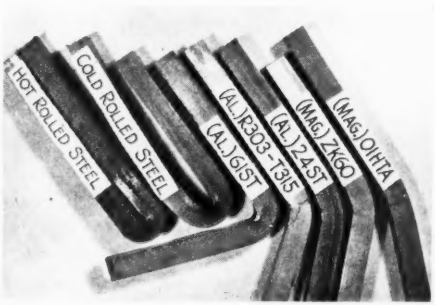

Plate II.

$\frac{5}{8}$in. square bars bent in the bending machine over a radius of $\frac{1}{4}$in. Left to right: Hot rolled steel, cold rolled steel, aluminium alloy 61ST, aluminium alloy R303-T315, aluminium alloy 24ST, magnesium alloy ZK60, magnesium alloy 01HTA.

possibilities, its strength being substantially the same as that of 01HTA. 01HTA shatters much like shrapnel, making testing rather risky. Without doubt much of this material has to be scrapped when extrusions of it are sprung into place in shop construction. No difficulties in testing were encountered with the aluminium alloys. Typical failures of these different alloys are shown in Plates III and IV.

As for the assumption of equalised moments, it is obvious that the moments should not always be assumed equalised. In the two load combinations used in the tests, the ratios in the elastic range of the two highest bending moments were only 1.2 and 1.5 (Figs. (g) and (e)). Suppose such a ratio were 3 or 5 or even higher, no definite answer can be given as to what might occur. This must await a more perfect definition of ductility. It can only be said that the more ductile the material the higher is this ratio for which unity may be assumed in the limit. In extreme cases an idea of how large or how small this ratio should be assumed, could probably be gleaned from the assumed elastic behaviour of the beam. This ratio will be close to unity, or much greater than unity, depending on whether the material has much or little ductility. For extremely brittle materials there is no question but that the elastic limit stress should control in the design, that is control in the strictest sense. For a very ductile material like mild steel there is no necessity of referring to the elastic behaviour. A test, which has not been reported here, was run on a steel bar as a continuous beam on four supports in which the ratio of the two highest bending moments was about 3.7. The load based on equalised moments was not only completely realised, but the beam carried an even higher load.

Much has been written on the subject of what happens and how it happens at the one critical section in a simple beam when the fibres are stressed beyond the proportional limit. Nadai,[19] Timoshenko,[14] and more recently Scott,[20] Cozzone,[15] Rappleyea and Eastman,[21] and Peterson,[22] to mention but a few, have contributed to this subject. In the final application to the design of structures, however, this study, like the study of the stresses at the junction of the web and the flange in an idealised I-section, is just an interesting detail. The really important thing to know is *what* a section contributes, *when* in the course of loading is it contributed, and *how long* is it contributed in the

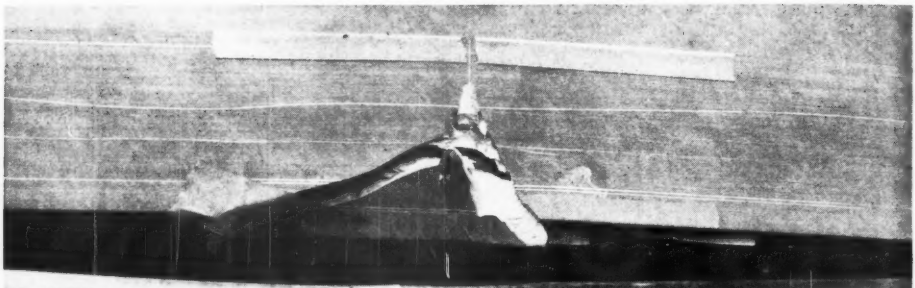

Plate III.
Typical local failures of magnesium alloy 01HTA I-extrusions.

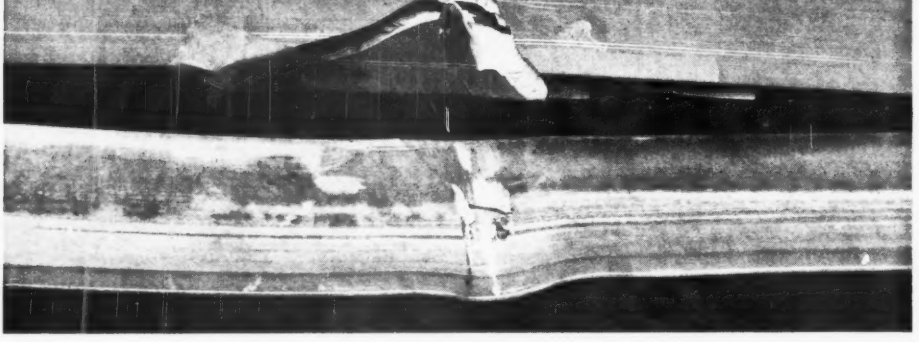

Plate IV.
Typical local failure of aluminium alloy 61ST I-extrusions.

functioning of a redundant structure of which it is an integral part. The most sensitive feeling for the physical is essential in order to appreciate fully the interaction between the redundants and the "primary" system in a highly complex structure.

In conclusion then it may be said that:

(1) The simplified methods of Limit Design, developed for specific application to steel structures, can be applied with safety to structures made of the alloys of magnesium and of aluminium, provided that some suitable value of stress be used in lieu of the yield point stress in steel.

(2) The peculiar shape of the stress-strain curves of the light metals actually constitutes an advantage in that relatively higher loads can be carried by redundant structures of the

light metals (as compared to similar non-redundant systems) than can be carried by redundant steel structures (as compared to similar non-redundant systems).

(3) The comparative brittleness of the light metals, however, constitutes a distinct disadvantage, which cannot be clearly reduced to exact figures until an answer is found to the question: What is the minimum of ductility consistent with safety, considering the differences in the requirements of various constructions?

(4) Thought should be given to adopting a criterion of strength more logical than the elastic limit stress. For the present there does not seem to be a more logical yardstick than the elastic deflections of non-redundant systems.

ACKNOWLEDGMENT.

The writer takes this opportunity to express his indebtedness to the following:

To Dr. John C. McDonald of the Dow Chemical Company, who was chiefly instrumental in furnishing a generous supply of Dowmetal magnesium alloy extrusions; to the Reynolds Metals Company for a similar supply of aluminium alloy extrusions; to Messrs. Marvin Hamilton, Risden Curry, and especially Milo Kaufman, for their assistance in the laboratory; to Professor E. L. Eriksen for his understanding of the testing requirements and his co-operation in securing the needed laboratory instruments; to Professor J. A. Van den Broek, to whom this work is dedicated, for his untiring interest, sympathy, and encouragement; and to Mr. Arthur Witting for his valuable criticisms and help in the preparation of the manuscript.

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REFERENCES.

1. A. Wolf, A History of Science, Technology, and Philosophy in the 16th and 17th Centuries, The Macmillan Co., 1939.
2. A. Wolf, A History of Science, Technology, and Philosophy in the 18th Century, The Macmillan Co., 1939.
3. Isaac Todhunter and Karl Pearson, A History of the Theory of Elasticity and of the Strength of Materials, Vol. I, Cambridge University Press, 1886.
4. L. Euler, Sur la force des colonnes, Memoires de l'Academie des Sciences de Berlin, Vol. XIII, 1759, pp. 252-282.
5. J. A. Van den Broek, Theory of Limit Design, Transactions of the A.S.C.E., Vol. 105, 1940, p. 638.
6. N. C. Kist, Ductility as a base for design-computation of steel bridges and structures instead of proportionality of stress and strain, International Congress for Metallic Structures, Liege, September, 1930.
7. H. F. Moore, The Strength of I-Beams in Flexure, University of Illinois Bulletin No. 68, Sept. 1, 1913.
8. Maier-Leibnitz, Beitrag zur Frage der tatsächlichen Tragfähigkeit einfacher und durchlaufender Balkenträger aus Baustahl St37 und aus Holz, Die Bautechnik, 1928, Heft 1, p. 11 and Heft 2, p. 27.
9. George Welter, The Yielding Phenomenon of Metals, Metallurgia, January-June, 1945.
10. J. A. Van den Broek, Rational Column Analysis, The Engineering Journal, December, 1941.
11. C. M. Goodrich, Limit Design, The Engineering Journal, January, 1940.
12. J. A. Van den Broek, Limit Design, The Michigan Technic, February, 1946.
13. J. A. Van den Broek, Theory of Limit Design, Journal of the Western Society of Engineers, Vol. 44, No. 5, 1939, p. 245.
14. S. Timoshenko, Theory of Elastic Stability, Engineering Societies Monographs, McGraw-Hill Book Co., Inc., 1936.
15. F. P. Cozzone, Bending Strength in the Plastic Range, Journal of the Aeronautical Sciences, May, 1943.
16. Structures Bulletin No. 25, Curtiss-Wright Corporation, January 1, 1944.
17. S. Timoshenko, Strength of Materials, Part II, D. Van Nostrand Co., Inc., August, 1941.
18. J. A. Van den Broek, Evaluation of Airplane Metals, The Engineering Journal, July, 1945.
19. A. Nadai, Plasticity, Engineering Societies Monographs, McGraw-Hill Book Co., Inc., 1931.
20. E. O. Scott, Deformations of Beams Involving Ductile Behavior (Doctoral Dissertation), U. of Michigan, 1940.
21. F. A. Rappleyea and E. J. Eastman, Flexural Strength in the Plastic Range of Rectangular Magnesium Extrusions, Journal of the Aeronautical Sciences, October, 1944.
22. F. G. Eric Peterson, Effect of Stress Distribution on Yield Points, Proceedings of the A.S.C.E., April, 1946.

CORRESPONDENCE

DESIGN FOR MAINTENANCE

I agree with the body of Lt. Bowden's paper (March 1947 Journal) and would like to stress the necessity for co-operation between maintenance and design personnel. Although I agree that the designer cannot meet everybody's requirements, I believe that design for maintenance should have equal place with design for manufacture.

An important side of aircraft maintenance omitted by Lt. Bowden is the electrical equipment. This is one of the main offenders in petty unserviceability. Electrical firms should try to increase the weather proofing of their equipment and help to cut down the endless earths.

With reference to the point about standardisation of spares for the same type of aircraft, but supplied by different contractors, I would like to defend the manufacturer to a certain extent. During wartime, because of the lack of plant, in many cases manufacturers had to use different methods. I know for a fact that whereas one firm would prefabricate an item another would prefer a casting. I think Lt. Bowden will agree that most of the aircraft he has met are of wartime manufacture and as a result the materials used (particularly metal alloys and rubber) and in some cases the workmanship were of an inferior quality. This would account for such things as hydraulic leaks. This is no excuse for inaccessibility and I would like to see access doors made so that the object to which one has (or is supposed to have) access, can be removed easily; in most cases this is impossible.

"Special tools" are the bug-bear of the maintenance engineer and I know of an aircraft which was unserviceable for a considerable period because a special extractor was required and the "one off" issued had broken and no other was available.

The keynote, I think, is co-operation.

Digby K. Harris, Graduate.

REVIEWS

The Aircraft Builders. An account of British Aircraft Production 1935-1945. H.M.S.O. 1947. 9d. net.

What a magnificent story there is to be told of the Aircraft Builders during the ten years covered by this latest official production. And what a poor story has been, to quote from the title page, "prepared for the Ministry of Aircraft Production (now incorporated in the Ministry of Supply) by the Central Office of Information. Text by Nigel Balchin."

This is but the story of the scattered bare bones of a skeleton. Even those bones have not been gathered together in a form which might enable one to assert "This was once an aircraft builder." The bones are not worth ninepence. It is a pitiful waste of paper to publish at the present time such an amorphous mass of words when there is such a demand for worth-while reading.

If the author had gone into the aircraft factories, if he had talked to the machine operators, the riggers and erectors, the designers, the sheet metal workers, the research workers, the managing directors, the skilled, the semi-skilled and the unskilled workers, the improvisors and the planners, the men and the women who did so much when so much was wanted to be done, the builders of aircraft, he could have told a story which would have gone the world over, which would have been forever remembered in the glorious sagas of this great country.

But the author didn't.

Tropical and Equatorial Meteorology. Maurice A. Garbell, D.Sc. Sir Isaac Pitman and Sons, Ltd., London 1947. £3 0s. 0d. net.

Man is a very localised individual normally. He is conditioned by his environment to an extent which he is the last to realise. He is a lucky individual who in his early years has the opportunity of becoming a cosmopolitan, and still more lucky if he ultimately can look upon the world as a whole as his environment. Then and then only does he rise above the state "when the weather gets him down," for he is well aware of what the general weather prospects are at any given period of the year in the particular country he happens to be in.

Up to now what is true of the ordinary man has been to some extent true of the meteorologist, although his field is larger in the beginning. But the normal meteorologist, quite naturally, has been largely concerned with weather predictions as they concern his own country.

With the increased world co-operation and the increased speed of communications and transport it has been realised how the weather in one part of the world has a vital effect upon the living conditions of people on the other side.

Dr. Garbell's book is all the more welcome as it is a broad survey of weather causes and conditions in the tropics which are now becoming of increasing importance to those living in the temperate zones. Part I is concerned with Fundamentals, as Circulatory Systems, Air Masses, Clouds, Cyclones and weather phenomena largely peculiar to the tropics.

Part II is more interesting, dealing as it does with regional tropical weather from Mexico to South Africa, from Pearl Harbour to the Panama Canal. In this Part the characteristic weather over some of the most important of the world's great air routes is described. Sooner or later from books, as the one under review, there will be prepared those general weather indications to pilots flying along the international routes which will be so necessary. And from such books, too, routes may be re-orientated to obtain the maximum benefits from the weather.

Tropical and Equatorial Meteorology is one of those books which pays constant dividends with study, and for aircraft designers it is one of those books which prove their value after the aeroplane has developed troubles in the tropics.

AN APPRECIATION

The Council of the Royal Aeronautical Society wish to thank those Companies who, by their generous co-operation, have done so much to help in the production of the Journal

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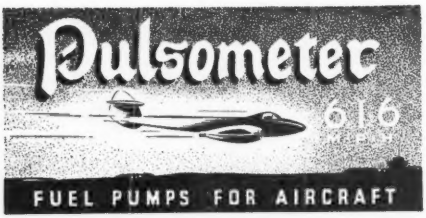

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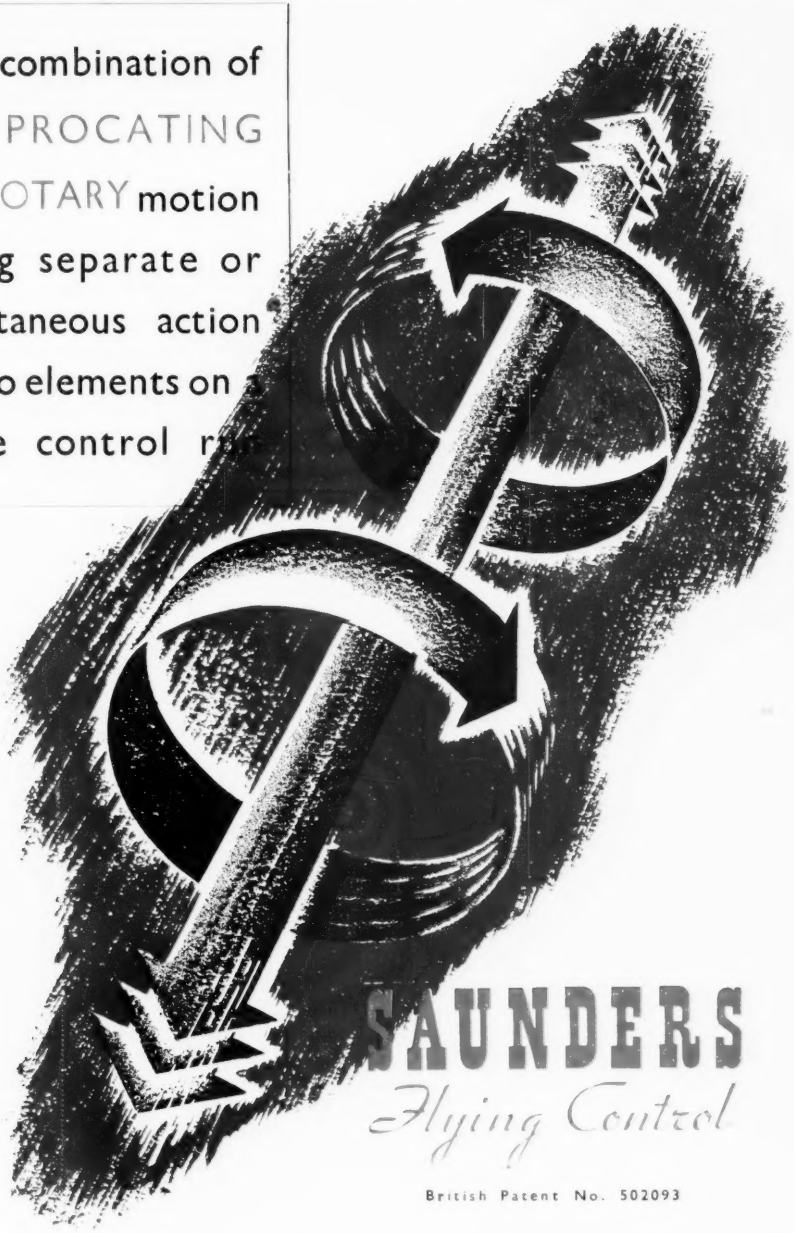

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